UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Overview of energy storage technologies for PV systems

Tânia Sofia Varela Santos

Dissertação

Mestrado Integrado em Engenharia da Energia e do Ambiente

2015

UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA

Overview of energy storage technologies for PV systems

Tânia Sofia Varela Santos

Dissertação

Mestrado Integrado em Engenharia da Energia e do Ambiente

Trabalho realizado sob a supervisão de

José Carlos Amador (Martifer Solar S.A.)

Jorge Maia Alves (FCUL)

2015

Resumo

Devido ao desenvolvimento tecnológico e às exigências da sociedade, o consumo de energia elétrica tem vindo a aumentar. Com esta procura, foi necessário desenvolver novas formas de produzir energia limpa, promovendo a diminuição de emissões de gases promotores de efeito de estufa e da utilização de combustíveis fósseis.

Uma vez que as energias renováveis são variáveis no tempo e não despacháveis, é impossível ter-se apenas produção de energia a partir de fontes renováveis. Para suprimir este problema, pode-se recorrer ao armazenamento de energia.

Esta dissertação teve como objetivo identificar e analisar as várias tecnologias de armazenamento de energia existentes. Foi feita uma comparação entre elas e identificada qual a tecnologia que se adapta melhor a um sistema fotovoltaico.

Posteriormente foi feito um enquadramento das várias tecnologias em vários tipos de aplicações, tais como, em aplicações comerciais e residenciais, aplicações em transportes, em aplicações off-grid e na aplicação para integração com energias renováveis.

Foi feita também uma análise do mercado existente e onde estão presentes as oportunidades de mercado (autoconsumo, retificação da rede e off-grid).

Por fim foi feito um estudo para três casos distintos, incluindo o dimensionamento de um banco de baterias. A escolha das baterias foi feita através da análise das suas características e custos.

Palavras-chave: Energias renováveis, Fotovoltaico, Off-grid, Armazenamento, Bateria.

Abstract

Due to a development in technology and society's requirements, the consumption of electrical energy has been increasing. With this demand, it was necessary to develop new forms of producing cleaner energy. This would consequently help promote a decrease in gas emissions, related to the greenhouse effect and to the utilization of fossil fuels.

Renewable energy is known to be variable in time and not dispatchable. For these reasons, it is impossible to obtain production of energy only from renewable sources. To suppress this problem, storing energy can be a resolution.

The purpose of this dissertation was to identify and analyze various existent technologies used in storing energy. They were also compared with each other. With the obtained information, one technology was identified as the most suitable for a photovoltaic system.

An outline of various technologies in various types of applications was elaborated. This includes commercial and residential applications, applications in transports, off-grid applications and applications to integrate in renewable energies.

An analysis of the existing market and the location of market opportunities was also done (auto-consumption, grid rectification and off-grid).

Finally, a case study for three different cases was developed including the sizing of a battery bank. The choice of the batteries was done taking into account its characteristics and costs.

Keywords: Renewable Energies, PV, Off-grid, Storage, Battery**.**

Index

Figure index

Table index

Acronyms

EDLC	Electric Double Layer Capacitor
SMES	Superconducting Magnetic Energy Storage
PHS	Pumped Hydroelectric Storage
CAES	Compressed Air Energy Storage
TES	Thermal Energy Storage
PV	Photovoltaic system
DC	Direct Current
AC	Alternate Current
DOD	Depth of Discharge
BSOC	Battery State of Charge
FLA	Flooded Lead Acid battery
VRLA	Valve-Regulated Lead Acid battery
AGM	Absorptive Glass Mating battery
Ni-Cd	Nickel - Cadmium battery
Ni-MH	Nickel and Metal Hydride battery
SBB	Sodium – Beta alumina Battery
Na-Cs	Sodium - Cesium
Li-ion	Lithium Ion battery
EC-DMC	Electrolyte type
Li-S	Lithium – Sulfur battery
Li-air	Lithium – Air battery
IEM	Ion Exchange Membrane
FB	Redox Flow Battery
VRB	Vanadium Redox flow Battery
ZBB	Zinc Bromine flow Battery
PSB	Polysulfide Bromine battery
NTP	Normal Temperature and Pressure
FCV	Fuel Cell Vehicle
PVGIS	Solar photovoltaic energy calculator and solar radiation database.

PEM	Polymer Electrolyte Membrane fuel cell
AFC	Alkaline Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
UPS	Uninterrupted Power System
EV	Electric Vehicle

Nomenclature

P	Power	(W)
E	Energy	(Wh) or (J)
C	Capacity	(Ah)
V	Voltage	(V)
I	Current	(A)
η_C	Coulombic efficiency	(%)
t_c	Charge time	(s)
I_c	Charging current	(A)
t_d	Discharge time	(s)
I_d	Discharging current	(A)
η_V	Voltage efficiency	(%)
V_c	Charging voltage	(V)
V_d	Discharging voltage	(V)
Cd	Cadmium	
OH^-	Hydroxide ions	
$Cd(OOH)_2$	Cadmium hydroxide	
NiOOH	Nickel oxide	
H_2O	Water	
e^-	Electron	
T	Temperature	(ºC)
MH	Metal hydride	
O_2	Oxygen	
La	Lanthanum	
Ce	Cerium	
Pr	Praseodymium	
Nd	Neodymium	
Ni	Nickel	
Co	Cobalt	
Mn	Manganese	
Al	Aluminum	
Ti	Titanium	
V	Vanadium	
Zr	Zirconium	

Cr	Chromium	
Zn	Zinc	
ZnO	Zinc oxide	
E^o	Cell potential	(V)
S	Sulfur	
Na	Sodium	
Li	Lithium	
$LiCoO_2$	Lithium cobalt oxide	
$LiPF_6$	Lithium hexafluorophosphate	
C	Carbon	
$LiFePo_4$	Lithium iron phosphate battery	
Li_2S_8	Cyclooctasulfur	
Li_2S_x	Polysulfide	
Br	Bromine	
Pb	Lead	
Fe	Iron	
H_2	Hydrogen	
V_2O_5	Vanadium oxide	
H_2S	Sulfuric acid	
ρ	Density	(J/kg)
L	Inductance	(H)
Ns	Strings number	
V_{DC}	DC voltage	(V)
V_B	Battery voltage	(V)
Np	Number of batteries in parallel	
C_N	Nominal capacity	(Ah)
C_B	Battery capacity	(Ah)
η_{inv}	Inverter efficiency	(%)
η_{cab}	Cables efficiency	(%)

1. Introduction

The search for electrical energy has shown to be increasing in the past few years. An increase in gas emissions, and the consequent greenhouse effect, leads to an inevitable search for sources of cleaner energies, in other words, renewable sources such as the sun and the wind. These energy sources present a problem however, since they are variable in time and, in general, will not completely fit the demand. For this reason, we need to use energy storage, that allows us to store energy that is produced by the renewable source during low-peak hours and, when necessary, inject into the grid during high-peak hours.

The focus on energy storage has been increasing in different sectors all over the world. In figure 1, the necessity for energy storage in Europe is shown. The residential sector reveals a significant increase in the search for storage relatively to the commercial sector. In 2016, it is expected that there will be about 220 MWh of storage capacity installed throughout Europe.

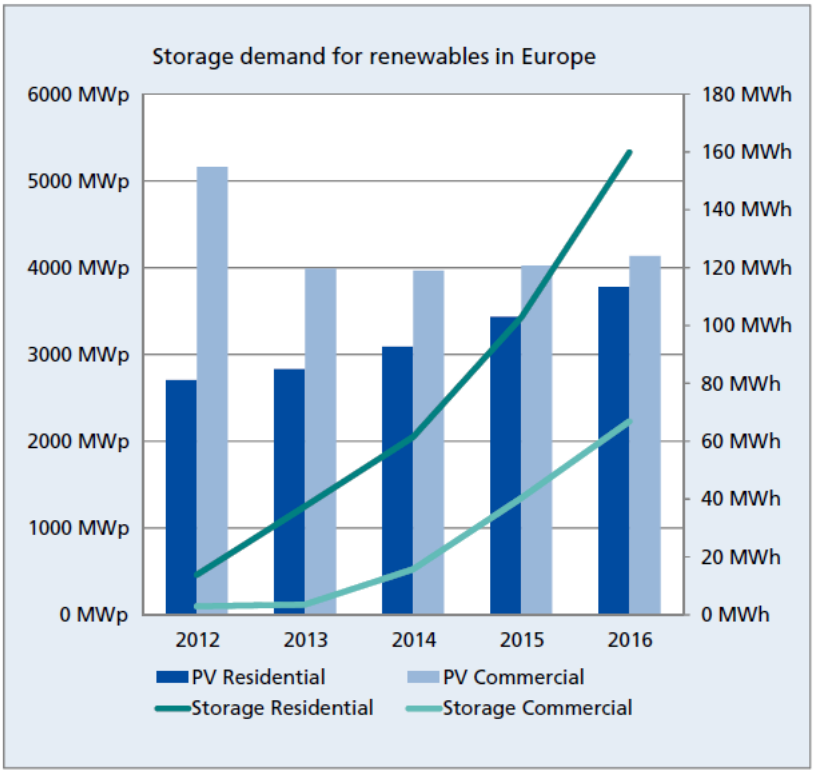


Figure 1- Storage demand for renewables in Europe [43].

Stored energy applications can be divided into two categories: *power quality and reliability* and *energy management.* In *power quality and reliability*, the stored energy is used in high power applications with relatively small energy content. The remaining applications of storage belong into the category of *energy management.* Figure 2 shows the storage technologies and the category they belong to.

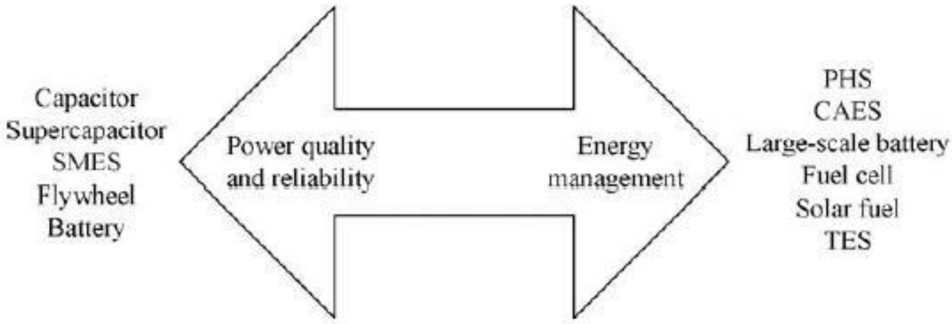


Figure 2- Classificação de tecnologias de armazenamento de energia consoante a sua função [1].

In the category *power quality and reliability*, we can find the *supercapacitors* (EDLC), the *superconductors* (SMES), the *flywheels* and the batteries. Other technologies including *reversible hydroelectric plants* (PHS), *compressed air* (CAES), large scale batteries, *fuel cells* and *heat storage* (TES) belong to the *energy management* category.

Due to the high cost of storing electrical energy, various forms of storage have been developed. Energy can be stored in the form of mechanical energy, including *PHS* and *flywheels*. It can also be stored in the form of thermodynamic energy, including *CAES* and *TES*, and in the form of electrochemical energy that includes all kinds of batteries and hydrogen (*fuel cells*). A last way of storing energy is in the form of electromagnetic energy that includes *SMES* and *EDLC*. Figure 3 demonstrates the discharge times and the application that each technology fits into.

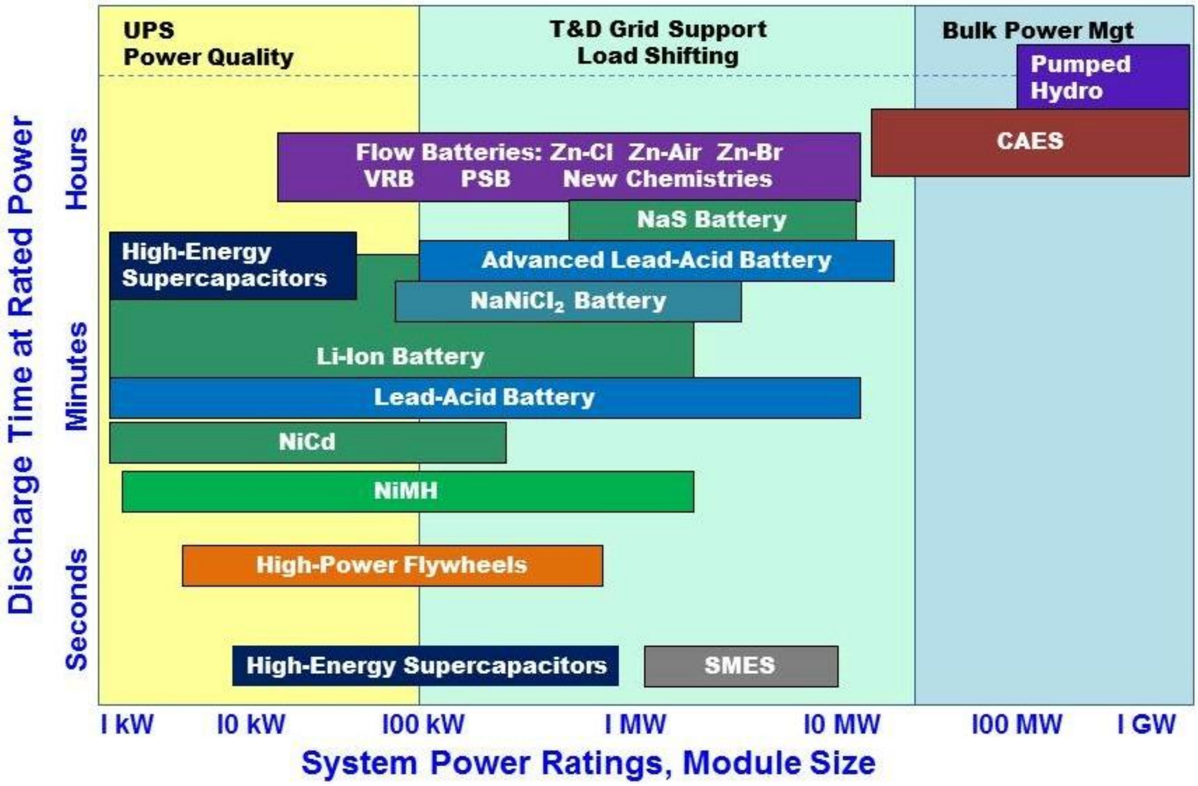


Figure 3- Comparison of different storage technologies [34].

However, most of these technologies are still being developed. Figure 4 illustrates the maturity of the different technologies.

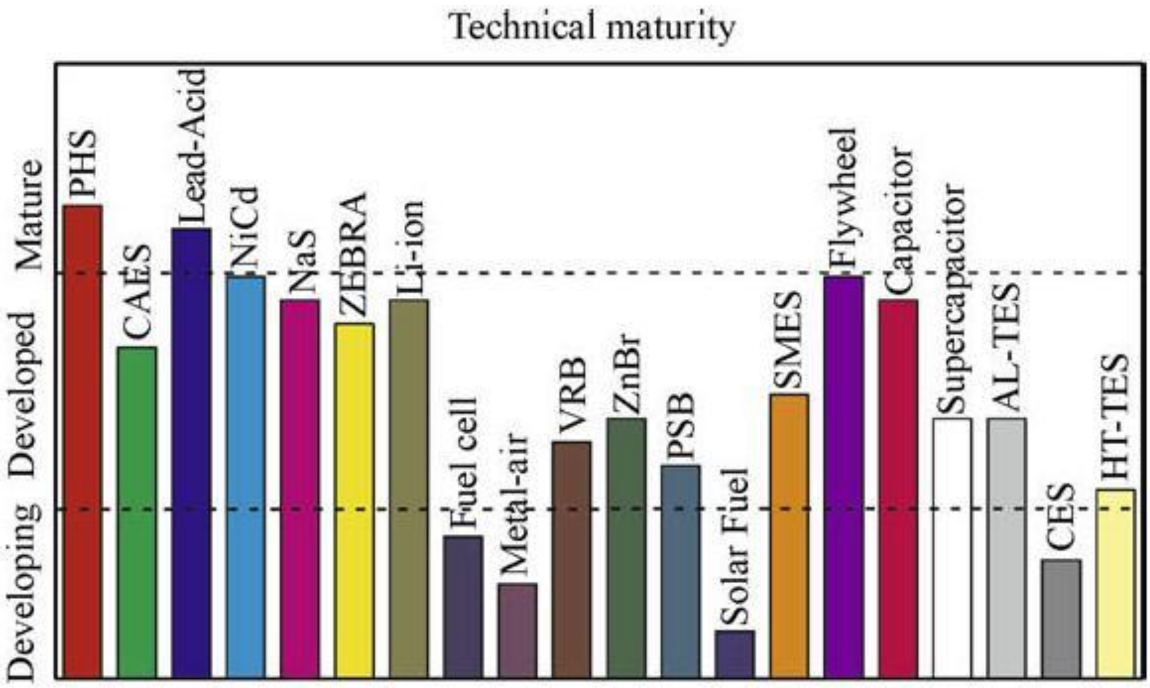


Figure 4- Technical maturity of different types of energy storage [35].

The purpose of this project is to conclude about the most suitable technology for electrical energy from renewable sources storage, more specifically, from photovoltaic panels (PV) that generate electricity directly from sun light. The photovoltaic panels convert solar energy into electrical energy in direct current (DC). If, for instance, batteries are used for storing this energy a charge controller must be used to protect the batteries. The charge controller is used to ensure that batteries are not overloaded and not discharged below a pre-determined depth of discharge (DOD), increasing therefore their lifetime. The charge controller will decide if the charge will be stored or not, depending on the charge state of the battery. Figure 5 shows an example of a scheme of a PV system with a bank of batteries, a charge controller, and an inverter to generate 230V AC current.

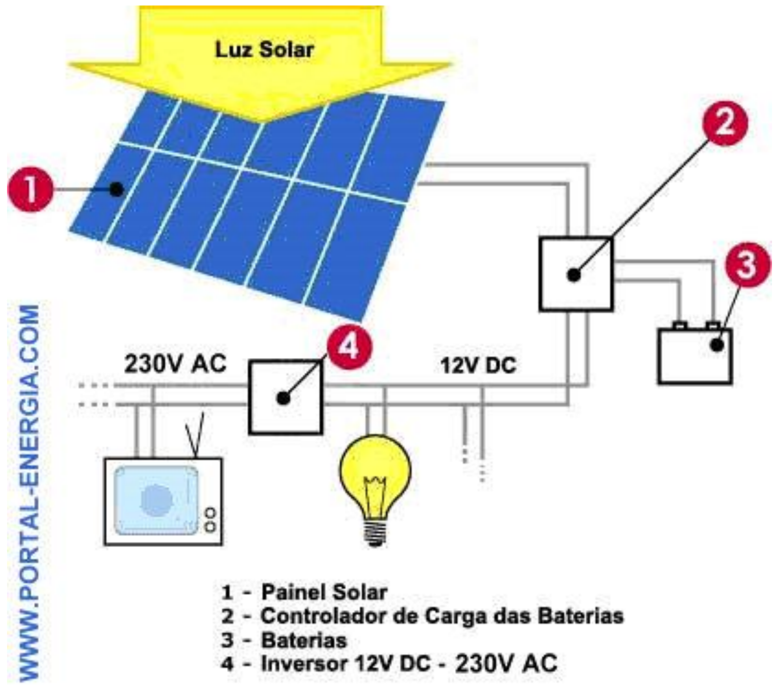


Figure 5- Esquema de um sistema PV com baterias [2].

2. Energy storage technologies (State of the art)

2.1 Storage of mechanical energy

2.1.1 Reversible hydroelectric facilities (PHS)

This type of storage is done by increasing the water potential energy when the energy generation exceeds consumption, raising it to a reservoir located at a height *h*. A fraction of this energy can be recovered through a turbine coupled to a generator, when production does not meet consumption (figure 6).

Due to its large capacity this energy storage technology is used in high power applications (MW). It presents a low cost per cycle, however, the initial investment and maintenance costs are very high, since it is necessary to have special landscape conditions.

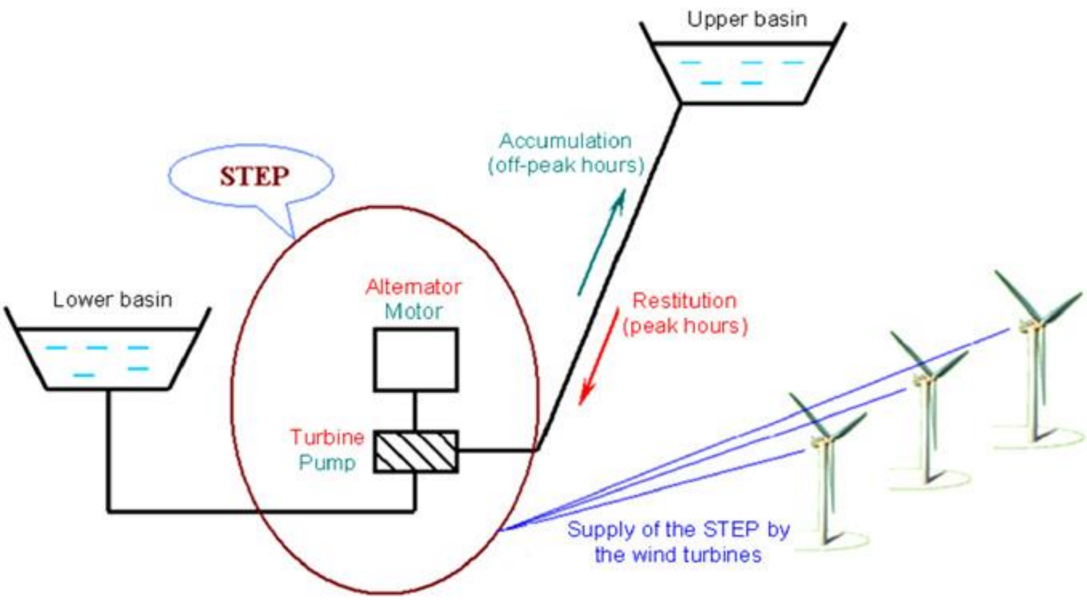


Figure 6 - Illustration of reversible hydroelectric facilities [3].

2.1.2 Wheels of inertia

The wheels of inertia, also known as *flywheels*, store energy in a rotating mass. A quantity of kinetic energy is stored as rotational energy, which depends on the inertia and the speed of rotational mass. This kinetic energy is transferred into and out of the steering wheel, which is inside a vacuum container to eliminate the air friction losses and suspended by bearings to a more stable operation. This transfer is done via an electric machine which can operate as a motor or generator, depending on the phase angle. When operating as a motor, the power supplied to the stator winding is converted to binary and applied to the rotor, making it spin faster and gain kinetic energy. The figure 7 shows the layout of a *flywheel*.

The *flywheels* are able to respond quickly, both on charging and discharging, but are unable to have high storage capacity (figure 3). This makes them more suited to grid quality control. They also have little resistance to external mechanical shocks which cause vibrations and result in loss of power, the output voltage and frequency have large amplitude variations and features gyroscopic effect.

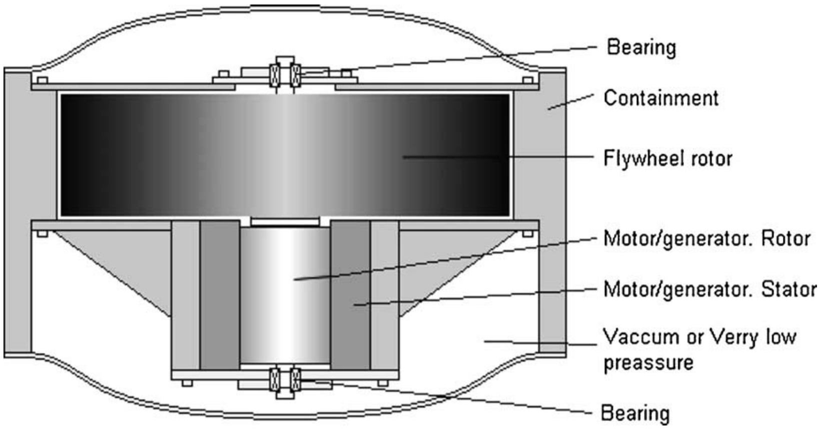


Figure 7 - Layout of a flywheel [4].

2.2 Storage of thermodynamic energy

2.2.1 Compressed air (CAES)

CAES uses a standard gas turbine, which uses about two-thirds of the available energy for compressing the combustion air in an underground cavern. The energy used to compress air is the excess power produced by the renewable, which will later be recovered by expanding the air in the combustion chamber then into the turbine (figure 8).

For the storage container be smaller, the air is compressed to high pressure (40-70 bar) and at temperatures near ambient [3]. Normally, ancient reservoirs of salt mines or natural gas, which are embedded in rocks of high quality for less losses possible of air mass.

From grid point of view the system efficiency is approximately 70% and the energy density is in the order of 12 kWh / m^3 [3]. However, this does not accounts for the fossil fuel energy (gas) that is used in the recuperator to heat the gas after adiabatic expansion. To reduce operating costs and have better efficiency, the system has to be controlled to minimize air leaks.

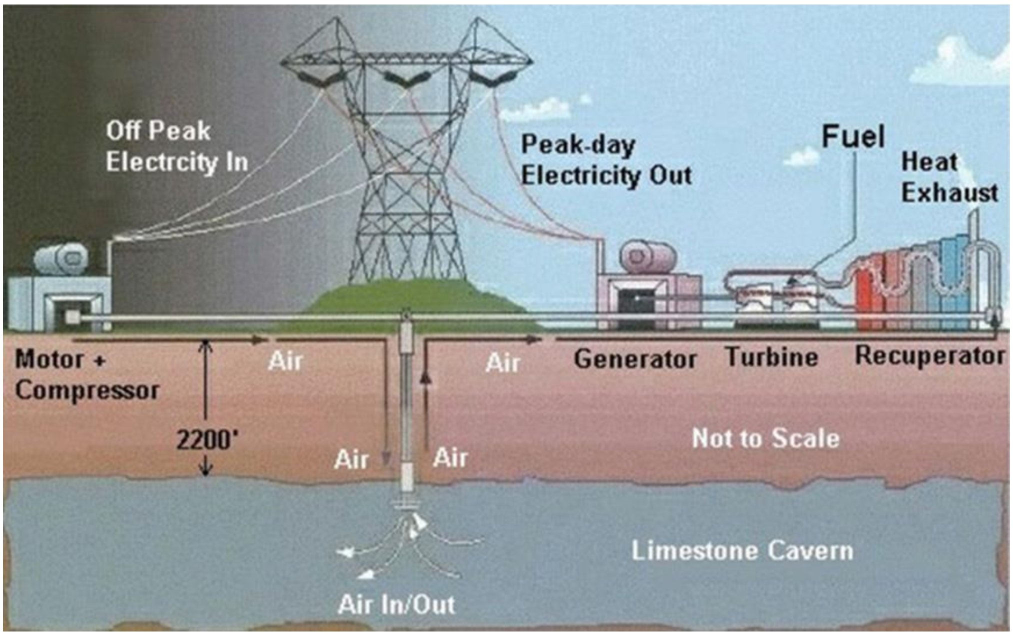


Figure 8- Illustration of CAES [3].

2.2.2 Thermal energy systems

Thermal energy can be stored as *sensitive heat* or as *latent heat*. Storage of *sensitive heat* is achieved by heating the core of a material that does not change its physical state. The heat is then recovered though the production of water vapor and conducted to an electricity producing turbine. *Latent heat* is stored through phase changes of the material. In other words, when a given material changes from solid phase to its liquid or gaseous phase, it stores a certain amount of energy during the process. The fact that there is a change in volume or pressure during this process could cause some difficulties for the tank.

Storage of latent heat presents higher energy densities in comparison to sensitive heat. This is so due to a higher enthalpy during changes of phases compared to enthalpy of a material at a determined temperature. Storing latent heat turns out to be very expensive, however, and after a certain number of cycles, the material ability to store heat begins to decrease. On the other hand, storage of sensitive heat has been very successful in its implementations. Currently, this technology has been used in big-scale applications with heat sources from solar towers [5]. Figure 9 demonstrates an example of *sensitive heat* storage.

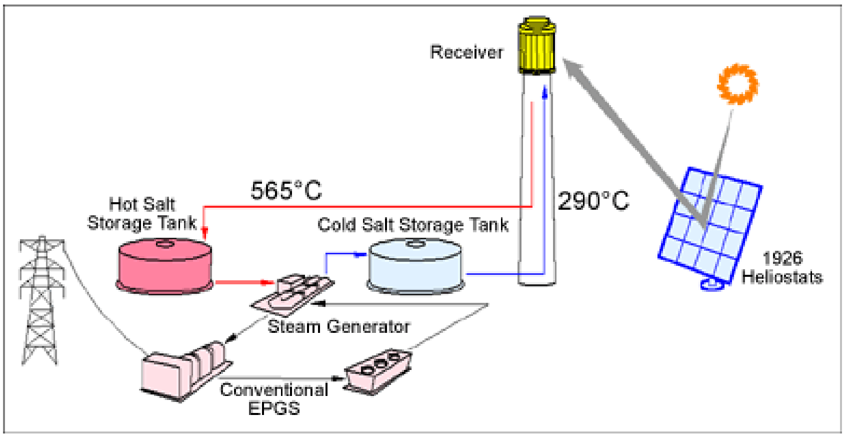


Figure 9 - Sensible heat storage system [6].

2.2.3 Systems with heat thermochemical materials

Storage of thermal energy in a chemical form has two main advantages: *i)*the significantly high density of the stored energy; *ii)* the fact that the energy may be stored for a long period of time with minimal losses. This technology, however, is still in development, searching for better charge and discharge efficiencies and lower costs [7]. An example of a thermo-chemical storage system is illustrated in the figure 10.

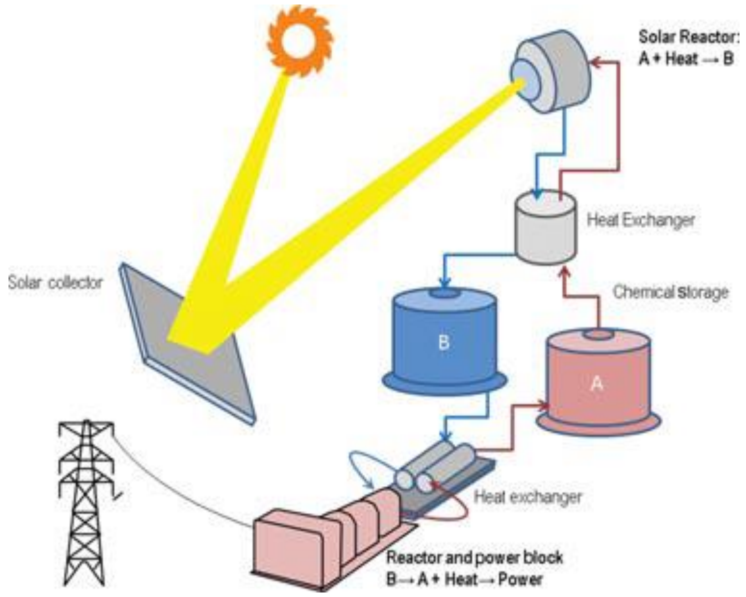


Figure 10- Thermochemical heat system [7].

2.3 Storage of electrochemical energy

2.3.1 Conventional batteries

Since batteries are the more common storage technology for PV systems, we will discuss deeply their working principle, their constitution, their characteristics, what type of batteries do exist and which one of them is more suited for this type of application.

Batteries are composed by a negative electrode (anode) and a positive electrode (cathode). The anode, during discharge, provides electrons to the load that is connected to the battery. The cathode accepts electrons from the load. There is also an electrolyte to complete the internal battery circuit that provides ions to the electrodes. This electrolyte has a separator that prevents the battery from experiencing short-circuit, and as a result, prevents the positive electrode to be in internal contact with the negative. This separator must be porous to allow for the circulation of ions from one side to the other. Figure 11 represents schematically the working principle of a battery.

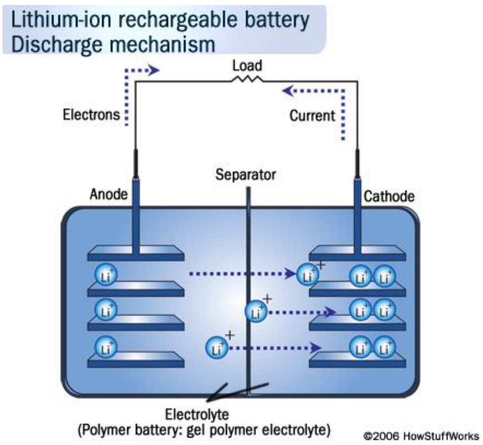


Figure 11- Diagram of the operation of a battery [8].

To obtain the desired capacity and output voltage, a multiple-cell battery is used, mounting the cells in series and in parallel. For best performances and to ensure maximum lifetime, the cells should all have the same capacity and, preferably, be, of the same brand and model.

All batteries have characteristics that define and distinguish themselves.

- *Battery voltage*

The single cell open circuit voltage is determined by the chemical reactions in the battery, the concentrations of the components and polarization. The nominal voltage is the output voltage value when the battery is in equilibrium conditions, the open circuit measured voltage.

When putting multiple cells in series, it is possible to obtain higher voltages, for instance putting 6 cells with a voltage of 2 V in series generate a battery bank that has a voltage of 12 V.

  - *Voltage variation with discharge*

The output voltage depends on the charge state of the battery and thus changes during the discharge time. This variation may be due to the conditions of discharge, the concentration levels and polarization. In figure 12, we can observe how typically the voltage changes with discharge time, for different battery types.

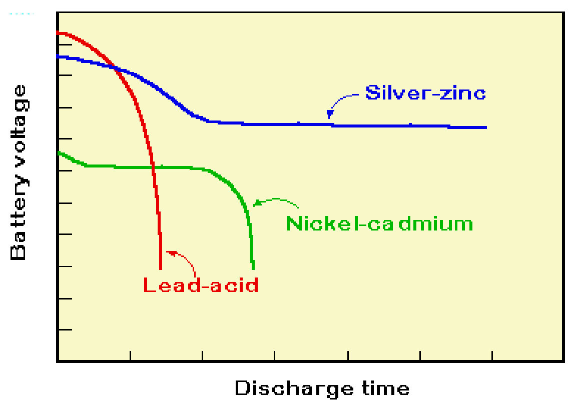


Figure 12- Variation of the voltage with discharge time [9].

- *Cut-off voltage*

All batteries should not be fully discharged because this decreases the battery lifetime and may lead to cell damage. For this reason, there is a level defined for how far they can be discharged. This level is called "cut-off voltage" a value that depends both on the type of battery and on temperature.

- *Effect of temperature on voltage*

With the increase of the system temperature, the battery voltage tends to decrease.

- *Battery charging and discharging parameters*

The battery characteristics changes with the number of cycles of charge/ discharge.

- *Battery state of charge (BSOC)*

The battery state of charge (BSOC) is one of the most important parameters of batteries. This is defined by the energy available taken as a percentage of the total battery capacity. For example, if a battery has a BSOC of 80% and a nominal capacity of 500Ah, the stored energy in the battery will be 400Ah.

- *Depth of discharge (DOD)*

As mentioned above, the battery should not be completely discharged. There is, therefore, a parameter called depth of discharge (DOD) which represents the fraction of energy that can be removed from the battery. The DOD value that does not compromise battery lifetime is provided by the battery manufacturer. Using DOD values higher than this, will decrease the lifetime of the battery and its capacity. On the other hand, the smaller the battery's voltage values, the greater its depth of discharge will be for the same amount of energy used.

- *Daily depth of discharge*

The Daily depth of discharge value is normally provided by the manufacturer. This value determines the maximum amount of energy that should be extracted from the battery in a 24 hour period.

- *Charging and discharging rates*

The rate of charge and discharge is represented in amperes (coulombs per second) and corresponds to the amount of energy added or removed from the battery per unit of time. That is, it determines the amount of time that the battery takes to charge or discharge completely. Typically this rate is represented by C/x, where C is the battery's capacity and x is the number of hours that the battery needs to charge or discharge.

- *Charging and discharging regime*

Each type of battery has different characteristics and different requirements for charging and discharging processes. For example, the nickel cadmium battery should be almost completely discharged before charging, while lead acid batteries should never be fully discharged. For this reason different charge controllers, should be used for different battery types, since the voltage and current during the charge cycle will be different.

- *Battery capacity*

The battery capacity represents the maximum amount of energy that can be extracted from the battery under specific conditions. However, when the battery is in different conditions, the real battery capacity can be different from the nominal capacity. The battery capacity changes with age, the regimes of loading and unloading and with temperature.

  - Units of battery capacity: ampere hours

The energy stored in a battery can be measured in different energy units, such as watt-hour (Wh), kilowatt-hour (kWh) and ampere hour (Ah). The most commonly used is Ah, which is defined as the number of hours the battery can deliver a current, that is equal to the discharge rate, at nominal voltage. The stored energy in *Wh* is the product of the load capacity *Ah* by the nominal battery voltage. These variables will change over the time, as the battery is used.

  - *Impact of charging and discharging rate*

The rate of charge and discharge affects the capacity of the battery. This phenomenon is due to the fact that the components necessary for the reaction do not have time to get into their positions and match up. Only a few ions will complete the reaction and then can recombine later. It is best practice to discharge the battery slowly, using a low current, since this way more energy can be extracted and the effective battery capacity will be higher.

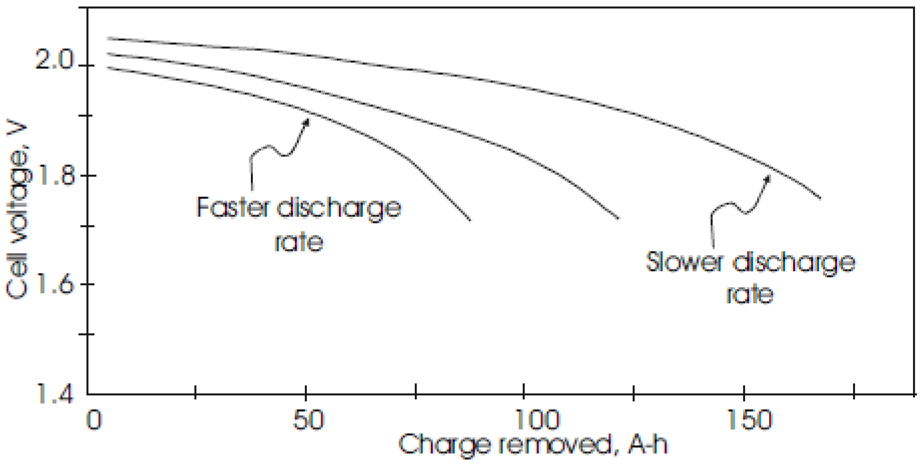


Figure 13- Effect of discharge rate on available energy from a lead-acid battery [10].

  - *Temperature*

The battery temperature also affects the battery capacity. In general, batteries at higher temperatures should have a higher capacity. However, when the battery temperature increases, there will be more losses due to Joules effect, which makes the battery capacity decreases and consequently its lifetime as well. The optimum operation temperature for the battery is specified by the manufacturer.

  - *Age and history of battery*

Both the age and how the battery was used have a major impact on the capacity. Even following the DOD specifications given by the manufacturer, the capacity of the battery will decrease with the number of charge/discharge cycles. If the battery has been discharged below the DOD, the battery capacity may decrease, as well as its lifetime.

- *Battery efficiency*

The battery efficiency is a very important parameter. It is the result of two efficiencies: coulombic efficiency and voltage efficiency. The global efficiency of the battery is the product of the two efficiencies.

  - *Coulombic efficiency*

The coulombic efficiency (η_c) is the ratio between the charge recovered during the battery's discharge and charge injected during the battery's charging. This efficiency may decrease due to losses caused by secondary reactions, such as water electrolysis. Normally, the coulombic efficiency is around 95% and can be determined using the following equation:

$$\eta_c = \frac{\int_0^{t_d} I_d dt}{\int_0^{t_c} I_c dt} \quad (1)$$

Where, t_d is discharge time, I_d is discharge current, t_c is charge time and I_c is charge current.

  - *Voltage efficiency*

The voltage efficiency (η_v) is the ratio between the average voltage during discharge (V_d) and the average voltage during charging (V_c).

$$\eta_v = \frac{V_d}{V_c} \quad (2)$$

We can then obtain a global efficiency of the battery:

$$\eta_B = \eta_v \eta_c = \frac{V_d \int_0^{t_d} I_d dt}{V_c \int_0^{t_c} I_c dt} \quad (3)$$

- *Energy, volumetric and power density*
  - *Specific and volumetric energy density*

The energy density is a parameter used to compare different types of storage technologies, in particular, different batteries. The volumetric energy density is the amount of electrical energy stored per unit battery volume, and is expressed in Wh/m^3. There is also a gravimetric energy density is given by Wh/kg, that is, the amount of energy stored per unit weight. For the same stored energy a battery having a higher energy density will be lighter than a battery having a lower energy density, which means, that this parameter is very important for portable systems.

  - *Power density*

The power density is an important parameter for applications where dispachability is important, such as for transports, however it is not very important for photovoltaic systems. This parameter is related to the ability that the battery has to discharge faster and the energy density.

- *Other electrical battery parameters*
    - *Internal series resistance*

The internal resistance of the battery determines the maximum current of the discharge and also Joule losses during charge/discharge processes. For applications which require the battery to provide a high instantaneous power, the internal series resistance must be low. This resistance will also affect the efficiency of the battery, but this can change over the lifetime of the battery.

- - *Self-discharge*

The self-discharge refers to the loss of charge when the battery is not being used, which means, when the battery is not connected to the network system, the battery will discharge over the time. This phenomenon is due to the materials involved in the chemical reaction and the battery temperature. Normally the manufacturer specifies the loss of charge per day or per month.

- - *Cold cranking current*

This parameter is not very relevant for photovoltaic systems but it’s for transport applications, since the battery has to supply a huge amount of current to start the engine. This parameter refers to the maximum amount of current the battery may deliver in a short period of time.

- - *Temperature effects*

All batteries lose capacity with decreasing temperature. Some types of batteries are sensitive to cold and may even suffer irreversible damage if freezing.

- *Battery Lifetime*

Batteries lifetime is expressed in cycles of charging/discharging or years. Normally, the lifetime is given in number of cycles when the battery is frequently used. When the battery is used in a system which is only used sporadically, being always connected to the network, its lifetime is presented in years. When the battery is not used properly and is not in perfect conditions, the lifetime may decrease dramatically.

- *Maintenance requirements*

In general for the battery to have a longer lifetime maintenance procedures are needed. Maintenance free batteries are available in the market today. The required maintenance procedure for each battery type is specified by the supplier.

- *Safety*

Most batteries use dangerous and corrosive chemicals, which means, that batteries must be installed in ventilated and protected places.

- *Battery disposal*

When the batteries reach their end of life, they need to be recycled because they contain toxic and corrosive materials, which can be dangerous for the environment.

2.3.1.1 Lead acid batteries

Lead acid batteries are the most commonly used batteries in many applications including in photovoltaic systems.

The lead acid batteries use an anode made from porous or spongy lead, which favors the formation and dissociation of lead, and a cathode made from lead oxide. The electrolyte is an aqueous sulfuric acid solution. The energy is stored by the reversible chemical reaction shown below.

During discharge the main reaction at the anode (negative terminal) is

$$Pb + {HSO_4}^- \rightarrow PbSO_4 + H^+ + 2e^- \tag{4}$$

At the cathode (the positive terminal during discharge) the corresponding reaction is

$$PbO_2 + 3H^+ + {HSO_4}^- + 2e^- \rightarrow PbSO_4 + 2H_2O \tag{5}$$

The global reaction is

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O \quad (E^0 = 2.04V) \tag{6}$$

By discharging the battery lead sulfate crystals formation and liberation of valence electrons of lead will occur on the electrodes. This formation of crystals results from the dissociation of the sulfuric acid from the electrolyte of the battery, which makes it less concentrated. When the discharge is complete, both electrodes become covered by the same material: lead sulfate. This way, there will not exist a cell voltage between the two electrodes. Under proper use, however, the battery should not be completely discharged. For this reason, discharging must be stopped once the cutoff voltage is reached. When the battery is left with low charge for a long period of time, the lead sulfate crystals may grow. This results in a battery with reduced capacity.

The most important characteristics of the batteries that are used in battery banks for PV systems are the depth of discharge and the battery capacity. These two characteristics are always found alongside one another since the energy extracted from the battery is the result of the multiplication of the capacity of the battery by the depth of discharge. The batteries can be classified as deep-cycle or shallow-cycle. Deep-cycle batteries may have a depth of discharge between 50% and 80%. As for the bank of shallow-cycle batteries, for these to reach the same available energy as the deep-cycle batteries, they will need a higher capacity since they have smaller cycles. The following figure shows the dependence of battery capacity on the number of cycles and the corresponding depth of discharge for a shallow-cycle lead acid battery.

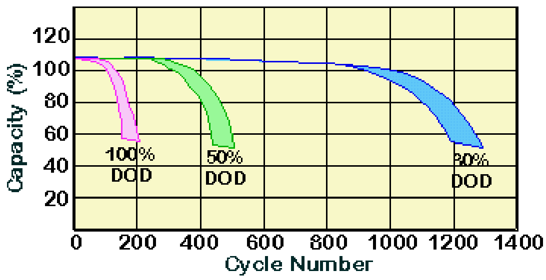


Figure 14 - Variation of capacity with cycle numbers and DOD for shallow-cycle lead acid battery [9].

By analyzing the figure 14, we can conclude that the lower the depth of discharge of the battery, the higher the number of cycles the battery will sustain. In other words, the lifetime of a shallow-cycle battery increases with DOD decrease.

A deep-cycle lead acid battery, may have a lifetime greater than 1000 cycles, even with a DOD higher than 50%.The lifetime of the battery does not change only due to discharge, but also due to the charging system. In the figure 15, it is possible to verify the impact that this effect has upon the capacity of the battery.

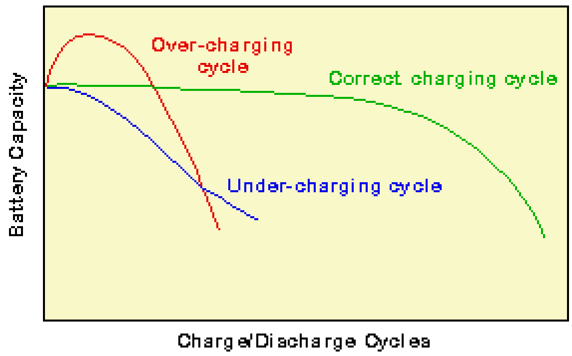


Figure 15- Impact of charging regime of battery capacity [9].

In the figure 16, it is possible to see the dependence of battery capacity on discharge rate and temperature. For each degree below 20ºC, the capacity decreases 1%. However, it is not ideal for the battery to work at high temperatures since this will accelerate the ageing, the auto-discharge and the electrolyte reaction. The ideal would be to discharge the battery as slow as possible and at room temperature (25ºC).

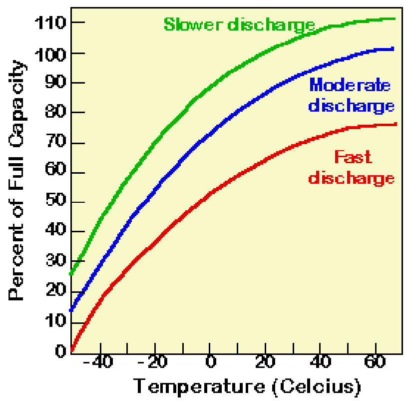


Figure 16 – Variation of battery capacity with discharging rates and temperature [9].

In the figure 17, we can observe the impact of the temperature and of the DOD upon the lifetime of a battery.

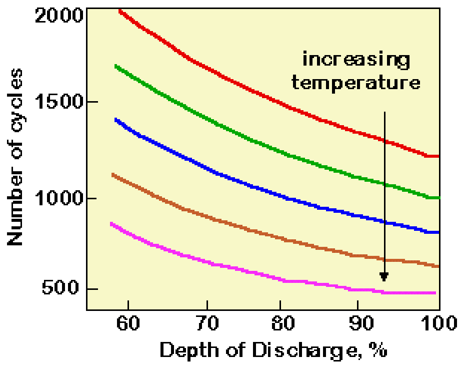


Figure 17 - Impact of battery capacity with DOD and temperature [9].

The general conclusion is that battery lifetime decreases with the working temperature increase and also with the increase in depth of discharge.

The lead acid batteries normally present efficiencies in the order of 70%, with columbic efficiency rounds 85%. For the batteries not to decrease their efficiencies drastically, it is necessary to perform maintenances. Due to the production and liberation of hydrogen and oxygen during the chemical reactions associated to charge and discharge, the battery will suffer loss of water, being therefore necessary its reposition. In the next table the advantages and the disadvantages of lead acid batteries are summarized.

Advantages	Problems
No maintenance	Low specific energy
Low self-discharge range	Long charge
Cheap and easy to manufacture	Limited lifetime
High specific power	Harmful for environment
Good performance at high and low temperatures	

One of the most important characteristics of storage for a PV system is the battery lifetime because solar panels have a demonstrated lifetime period of about 25 years. Therefore, the most suited batteries are the deep-cycle batteries. Within this category, there are flooded lead acid batteries (FLA) and valve-regulated lead acid batteries (VRLA).

Flooded lead acid battery

The FLA batteries are the most popular batteries in the photovoltaic systems. The term “flooded” is due to the fact that the battery has excess electrolytes, which results in the electrodes being completely submersed. In a lead acid cell the lead and diluted acid undergo a chemical reaction that produces lead-sulphate and water during discharge. During charging, the lead-sulphate and water are turned back into lead and acid. The re-dilution of sulphuric acid that occurs during charge is a highly exothermic reaction. If this heat is not efficiently removed the battery will reach a sufficiently high temperature (mainly if excessive charge current is used) and the diluted acid will be broke down into its component parts: sulphur, hydrogen, and oxygen. In flooded lead-acid batteries, the sulphur sinks to the bottom of the cell while the oxygen and hydrogen gases are allowed to escape, and so the cells must be regularly refilled with water to compensate for the outgassing H and O losses. FLA batteries are more tolerant to this outgassing because the level of electrolyte is never below the electrodes, preventing this way, battery damages. These batteries have advantages and disadvantages, which will be represented in the table below.

Advantages	Problems
Lower cost than VRLA batteries	Periodic maintenance
Longer life time than VRLA batteries	Can only be used in one position (upright)
Simple maintenance by addition of distilled water	Production of gas when charging
High discharge rate	May emit acid spray if overcharged
Good performance in hot climates	Require ventilation
Better performance than VRLA batteries when state of charge is partial	Higher self-discharge rate than VRLA batteries
	Cannot be shipped by air
	Cannot be used in the proximities of electrical equipment or anything high flammable

Valve-regulated lead acid battery

The main difference between FLA and VRLA batteries, is that in the valve-regulated lead acid batteries the already mentioned outgassing only occurs if a security level of pressure inside the batteries is achieved. Only when this happens outgassing is allowed by that valve. As a consequence, this type of batteries do not need maintenance and may be used in any position.

The VRLA batteries do not need addition of water since the oxygen produced in the cathode, during battery charge, migrates to the anode where it combines with hydrogen into water. As this process is not 100% effective, oxygen and hydrogen gases will be found inside the battery, which will exert a pressure upon the battery. This excess of pressure will activate a valve that ventilates the battery, eliminating the gases. It is for this reason that the battery is denominated valve-regulated and not sealed battery. Nevertheless outgassing being much lower, a loss of water still occurs and, consequently, a permanent damage of the battery may happen, namely if charging currents are high.

The migration of oxygen that is necessary for the recombination with hydrogen into water can be done via two processes:

Absorptive Glass Matting (AGM) battery

The AGM batteries use a porous separator of matt glass that has the ability to absorb a large quantity of electrolyte. At the same time, this separator will leave some pores unfilled which will serve as a passageway for the oxygen.

As with all battery technologies, this represents some advantages and disadvantages.

Advantages	Problems
Less expensive than Gel batteries	Don't perform as well as FLA or Gel batteries for systems that require regular deep of discharge. (i.e. 80% DOD)
Large temperature range than Gel or FLA batteries	Don’t perform as well as Gel batteries in low power applications
Low self-discharge	
Best shock/vibration resistance	
Best for high power applications	

Gel battery

Gel batteries use a porous separator of matt glass linked to a porous polyethylene or polyvinylchloride sheet, as well as a thyrotrophic gel electrolyte of silica mixed with sulfuric acid. When an electrolyte is added, the pores of the separator will be all filled, thus not leaving any space for the passage of oxygen. This way, initially, the battery will function as a flood battery, outgassing will occur, and there will be loss of water. Due to this occurrence, the gel on the separator will dry, shrink and crack, allowing then, the passage of oxygen to the anode.

The advantages and disadvantages of the Gel batteries are represented in the following table:

Advantages	Problems
Better perform than AGM batteries for systems that require regular deep discharge (i.e. 80% DOD)	More expensive
Better performance than AGM batteries for low power applications	Don’t perform as well as FLA or AGM batteries in cold temperatures
	Don’t perform as well as FLA or AGM batteries when they regularly reach a shallow depth of discharge. (i.e. 20% DOD)
	Higher self-discharge rate than AGM batteries

2.3.1.2 Nickel - cadmium batteries (Ni-Cd)

The nickel cadmium battery is constituted by a cathode of nickel oxide hydroxide, a cadmium metal anode and an electrolyte of potassium hydroxide. In the reaction shown below, it is represented how the energy is stored.

The main reaction at the anode, during discharge is

$$Cd + 2OH^- \rightarrow Cd(OH)_2 + 2e^- \tag{7}$$

At the cathode, the corresponding reaction is

$$2NiOOH + 2H_2O + 2e^- \rightarrow 2Ni(OH)_2 + 2OH^- \tag{8}$$

The global reaction is

$$Cd + 2NiOOH + 2H_2O \rightarrow Cd(OH)_2 + 2Ni(OH)_2 \quad (E^0 = 1.29V) \tag{9}$$

During discharge, on the anode, the cadmium oxidizes, connecting to OH^- ions coming from the cathode. Cadmium hydroxide and electrons are obtained and pass through the external circuit. On the cathode, a reduction of nickel oxide hydroxide occurs. When there is an intense discharge, it is probable that hydrogen will begin to form on the cathode. This hydrogen is consumed at a very low rate, which results in the pressure inside the battery increasing, and consequently leading to the battery's explosion. In the figure 18, we can observe more specifically the reactions that occur in the battery.

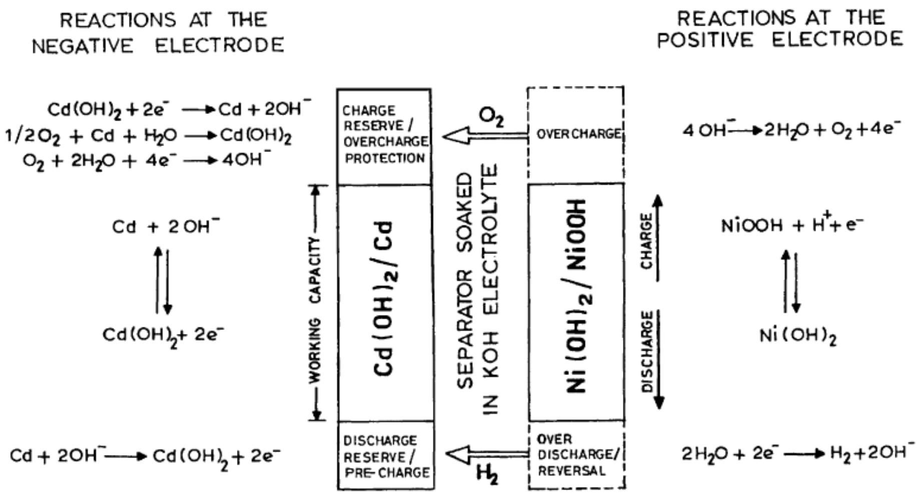


Figure 18- Operation principle of a Ni-Cd cell [11].

The performance of nickel cadmium batteries can change according to different factors, such as, the cell voltage, the operation temperature, or the charge and discharge rating. In the following figures, we can observe the variation of these characteristics during charge and discharge of the battery.

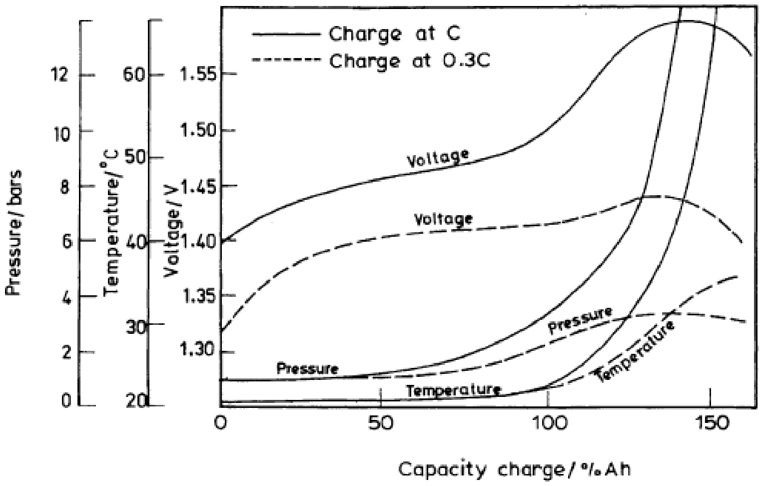


Figure 19- Relationship between battery capacity, voltage, pressure and temperature for different charge rates [11].

By analyzing figure 19, we can conclude that the slower the charge process, the more stable the battery will be as the voltage has a smaller variation, and both the pressure and temperature have less relevant increases.

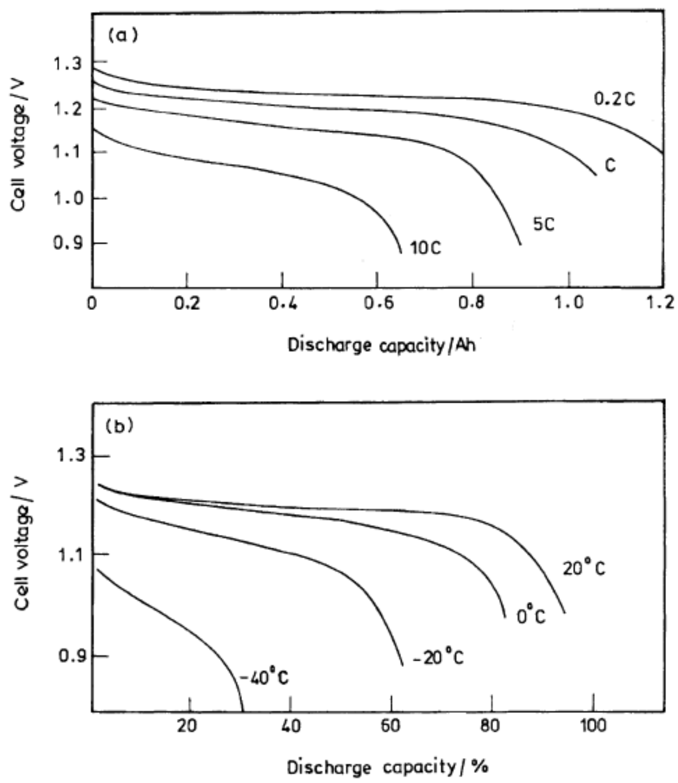


Figure 20- a) discharge curves for a typical 1.2Ah Ni-Cd cell at different discharge rates b) discharge curves for a typical Ni-Cd cell at different temperatures at C/2 rate [11].

Low discharge rates at a temperature of about 20ºCis recommended to obtain higher efficiency and longer lifetime.

The Ni-Cd batteries have a specific energy of about 50Wh/kg, which is 30% higher than with lead acid batteries, but still lower than more modern batteries. These batteries have been substituted by the nickel and metal hydride batteries, due to cadmium toxicity.

In the following table are represented some advantages and disadvantages from nickel cadmium batteries.

Advantages	Problems
Fast and simple charging even after prolonged storage	Low specific energy compared with newer systems
High number of cycles (over 1000 charge/discharge cycles with proper maintenance)	Memory effect
Good load performance	Cadmium is a toxic metal
Can be stored in a discharge state	High self-discharge
Simple storage and transportation	
Good low-temperature performance	
The most sheep in terms of cost per cycle	
Available in a wide range of sizes and performance options	

2.3.1.3 Nickel and metal hydride batteries (Ni-MH)

Nickel and metal hydride batteries are very similar to nickel-cadmium batteries. The difference is that the Ni-MH batteries use a metal hydride anode instead of cadmium. In the following reaction, we can see the global reaction of the discharge of the battery.

$$MH + NiOOH \rightarrow NiO(OH)_2 + M \qquad (E^0 = 1.35V) \tag{10}$$

At the anode, the corresponding reaction is

$$MH + OH^- \rightarrow H_2O + M + e^- \tag{11}$$

And at the cathode, the reaction is

$$NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^- \tag{12}$$

During discharge, on the cathode, NiOOH is reduced to $Ni(OH)_2$, just as on the Ni-Cd battery. On the anode, the metal hydride oxidizes, releasing water, a metallic ion and an electron that passes through the external circuit. During discharge, the inverse reactions occur. In the following figure, the reactions that occur in the battery are represented explicitly.

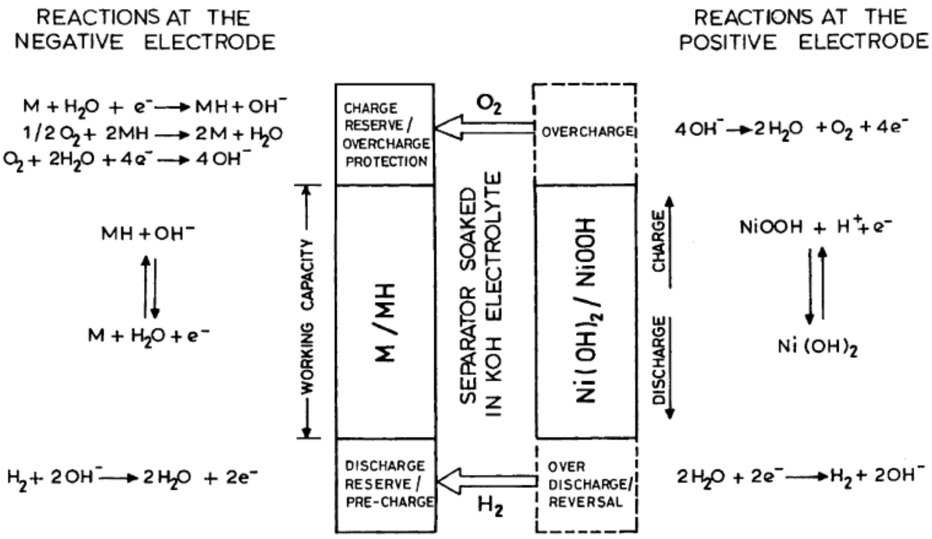


Figure 21- Operation principle for a Ni-MH cell [11].

M is an inter-metallic compound that connects different metals in combination. One of the compositions is AB_5, where A can be a combination of La, Ce, Pr and Nd, and B can be a combination of Ni, Co, Mn and Al. Another composition of M is AB_2, where A is the combination of de Ti, V and Zr, and B is a combination of Ni, Co, Cr, Mn, Al and Sn. Each combination offers different characteristics to the battery. This optimizes the battery through the best combination, allowing the battery to have a higher specific energy, more stability, better efficiency, higher capacity and a longer lifetime [11].

When an overload of the battery occurs, formation of hydrogen and oxygen begins, as in previous batteries. However, as the battery uses hydrogen in its reactions, it ends up compensating the hydrogen formed and maintains this way, a stable pressure. In addition to tolerance during overload, these batteries do not have a memory effect, do not form dendrites, and do not use toxic chemicals.

The following table lists some advantages and problems of these batteries.

Advantages	Problems
Better specific energy than Ni-Cd	Limited lifetime
No memory effect	Slow charge
Maintenance free	High self-discharge
Environmentally acceptable	
Recyclable materials	

2.3.1.4 Zinc-air batteries

Zinc air batteries are known for having a big potential but cannot yet be found in the market. These batteries use zinc on the cathode and oxygen, found freely in the air, on the anode. Since these batteries only use one electrode, they are able to reach very high specific energy values. The following equation shows this battery’s global reaction during discharge.

$$Zn + 2OH^- \rightarrow ZnO + H_2O + 2e^- \quad (E^0 = 1.26V) \tag{13}$$

The battery produces current when the anode is reduced with assistance of the catalyzer that produces hydroxyl ions on the electrolyte. The zinc is oxidized and releases electrons that create electric current. In the figure 22, a schematic representation of the battery during the charge process is shown.

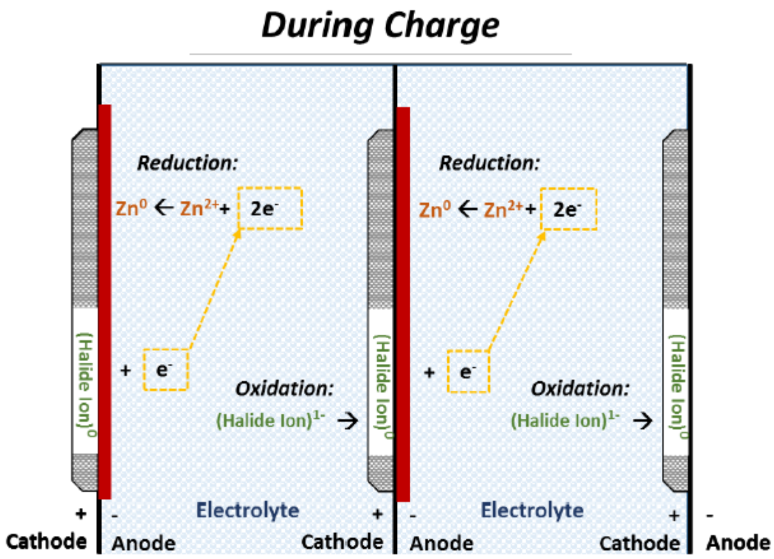


Figure 22- Scheme of charging Zinc-air battery [13].

A problem that is under investigation is the entry of carbon dioxide into the battery that may develop a negative impact on the electrolyte and on the cathode. The following table presents some advantages and problems found in these batteries.

Advantages	Problems
High specific energy	Low efficiency
Inherent safety	Susceptible to changes due to ambient air conditions
Long cycle life	
Low cost	
100% recyclable	

2.3.1.5 Sodium-Beta Alumina batteries (SBB)

Sodium-sulfur batteries are currently still under investigation. They present a potential to be used in stationery applications due to their long period of discharge (~6h).

The operational temperature of these batteries is in the range 300-350ºC. This results in the battery heat losses and may discharge when on standby. Ohmic heat will, however, compensate these heat losses allowing these losses to be considered as self-discharge. Sodium-sulfur batteries do not, however, present self-discharge due to their high efficiency [14].

The reactions that occur between sodium and melted sulfur are extremely exothermic. This causes an increased risk of the cell catching on fire, which would then cause the system to switch off the cell and consequently all string. For this not to happen, studies are being developed to ensure that the functional temperature of the battery decreases [14]. A recent published study showed that by using a sodium anode with cesium (Na-Cs), the battery's lifetime increases due to the fact that the operating temperature falls to the range 175-150ºC. Even with temperatures below 95ºC, the cell shows a good performance [17].

During discharge, sodium is oxidized and forms sodium ions. These migrate through the beta alumina electrolyte and connect with sulfur, which was reduced on the cathode, forming sodium polysulfide ($Na_2S_x,\ x = 3 - 5$). The following equation contains the battery's global reaction.

$$2Na + xS \rightarrow Na_2S_x \quad E^0 = 2.07 - 1.78V \tag{14}$$

In the following figure we can observe the structure of a sodium-sulfur battery.

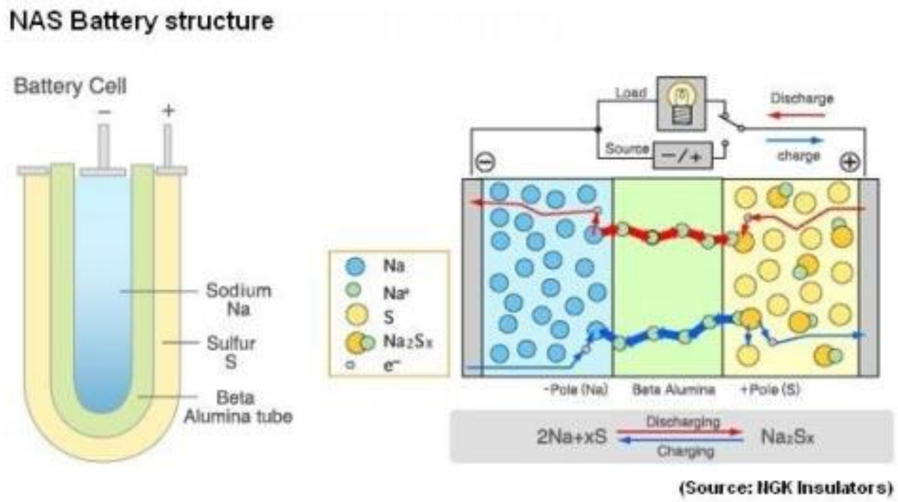


Figure 23 - SBB battery [18].

The following table shows some advantages and problems associated to sodium-beta alumina batteries.

Advantages	Problems
High specific energy	High production cost
Long lifetime	High resistance in cathode caused by sodium polysulfide formation
Low cost of materials	High resistance caused by membrane thickness
High efficiency	High self-discharge
High tolerance to overload	
Low maintenance	
Recyclable	

2.3.1.6 Rechargeable Lithium Ion (Li-Ion)

Lithium batteries are characterized by high specific energy, high efficiency and long lifetime. However, this technology appears problematic due to issues such us safety, cost, high operational temperature that may result in battery damage and limits to the materials availability.

These batteries are lightweight, compact and generate voltages of the order of 4V per cell, with specific energy ranging between the 100Wh/kg and 150Wh/kg. Currently the most used structure is the battery that has a graphite anode, a cathode of lithium metal oxide ($LiCoO_2$) and an electrolyte consisting of a solution of lithium salt ($LiPF_6$) mixed with an organic solvent (EC-DMC). In figure 24 we present a schematic view of a common lithium ion battery.

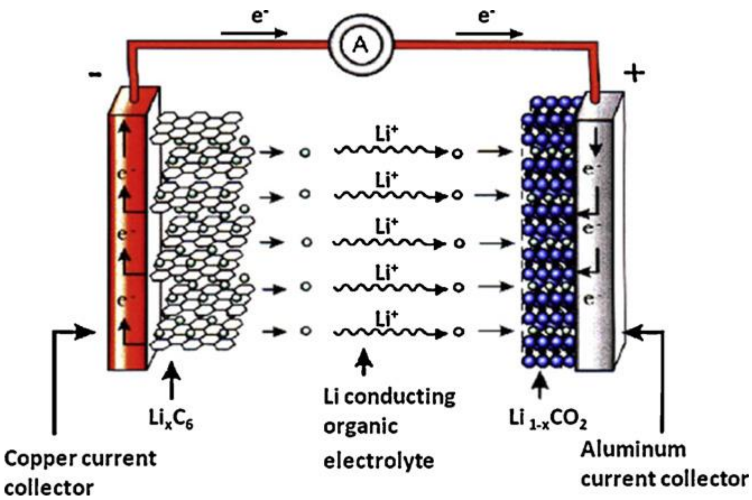


Figure 24- Li-ion battery [19].

The reaction that occurs in the battery, which is shown in the figure 24 is:

$$C_6 + LiCoO_2 \underset{discharge}{\overset{charge}{\rightleftarrows}} Li_{0.5}C_6 + Li_{0.5}CoO_2 \quad (E^0 = 3.6V) \tag{15}$$

During charging, the graphite is reduced and get in touch with the solution of lithium salt, the lithium ions reducing graphite. Meanwhile the lithium cobalt oxide will oxidize thus releasing electrons and lithium ions. During discharge, the reaction is reversed, as shown in figure 24.

Since the lithium ion batteries present a very high specific energy, their application is made mostly on low power portable technology. This is due to the reduced lifetime and low capacity. These batteries are therefore not advantageous for storage in renewable systems.

Advantages	Problems
High specific energy	When overloaded and overheated, the battery deteriorates, losing capacity which leads to a decreased lifetime. Overloading can cause fires and even explosions.
Low self-discharge	High internal series resistance
Low maintenance	Needs an external circuit of protection, for control the limits of voltage and current.
No memory effect	
Wide range of sizes and shapes for different applications	
Environmental friendly	

There are also other batteries of ion lithium where the cathode, the anode or the electrolyte can be differentiated. One of these batteries is the lithium iron phosphate ($LiFePo_4$) battery, where the cathode is changed to iron phosphate. Through this change, we can obtain a better electrochemical performance with low resistance, which allows the battery to have a good thermal stability, long cycles and to be safer. These batteries have a lower specific energy in comparison to the $LiCoO_2$ batteries, but higher in comparison to the lead acid, Ni-Cd and Ni-MH batteries.

2.3.1.7 Lithium - Sulfur (Li-S)

Lithium-sulfur batteries are still being developed since there is a necessity to improve their short lifetime and low capacity. However, these batteries present, theoretically, a high specific energy (2500Wh/kg) [20], which is five times higher than for ion-lithium batteries. This characteristic allows for them to be applied in electric vehicles (EV´s).

These batteries are made up by an anode of metallic lithium, a cathode of a metal containing sulfur, and an organic non-aqueous electrolyte. In equation 16 we present the global reaction of the battery.

$$2Li + S \rightarrow Li_2S \qquad (E^0 = 2.2V) \tag{16}$$

During discharge, the lithium ions go from the anode to the cathode through the electrolyte, where the formation of a big molecule of cyclooctasulfur (Li_2S_8) begins. At the end of discharge, the purpose is to attain Li_2S, although this result is not possible in only one step. For this, there has to be a long chain of lithium polysulfides (Li_2S_x, $4<x<8$) that will dissolve in the organic electrolyte transforming into insoluble Li_2S_2 and finally, into Li_2S. In figure 25, the process of charge and discharge of the batteries is schematically represented.

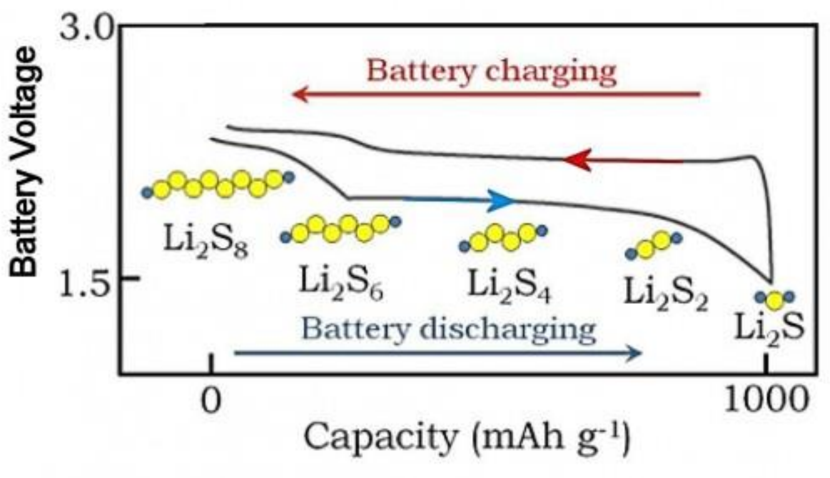


Figure 25- Charge/discharge process of Li-S battery [21].

In the following table, we list some advantages and problems present in lithium-sulfur technology batteries.

Advantages	Problems
High specific energy	Low sulfur conductivity
Full discharge	
Maintenance free	
Inherently safe	
Lifetime (1000 cycles)	
Environment friendly	

2.3.1.8 Lithium - Air (Li-air)

The lithium-air batteries are still not found in the market since they are still being developed. Its theoretical specific energy is in the order of 12,000 Wh/kg [22, 23], which makes them very promising in portable applications. This value finds itself very close to gasoline's specific energy value (13,000 Wh/kg) [22, 23], making them very competitive to the electric vehicle's market.

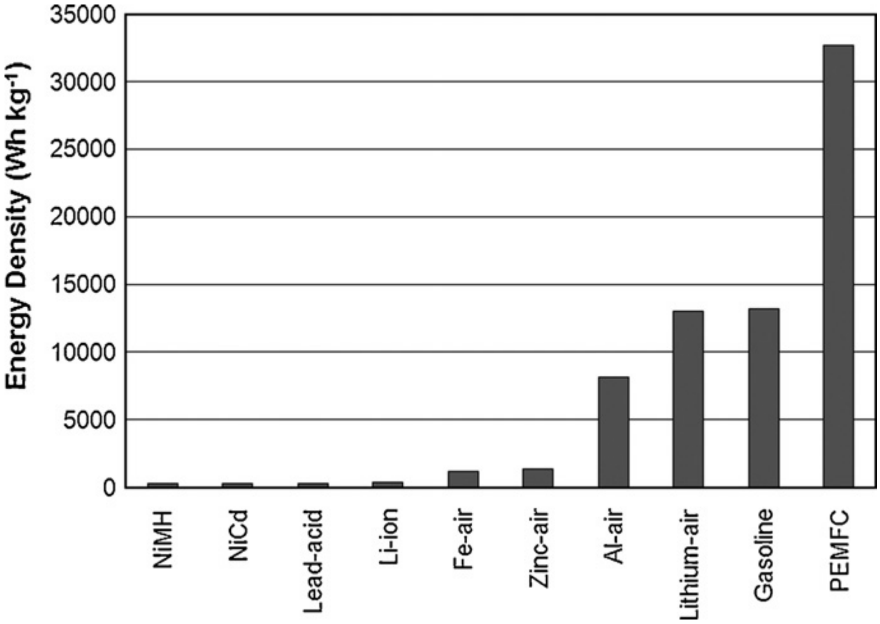


Figure 26- Comparing theoretical specific energy for different energy storage technologies [22].

These batteries are able to have a very high specific energy since the cathode's active material (oxygen) is not found stored in the battery. Since lithium has a specific capacity of 3500 mAh/g, which is superior to zinc's specific capacity (815 mAh/g), the lithium-air batteries turn out to be better than zinc-air batteries [24].

The battery is made up of an anode of lithium metal, a cathode of porous carbon for promoting diffusion of oxygen, and an organic electrolyte that may, or may not, be aqueous (figure 27).

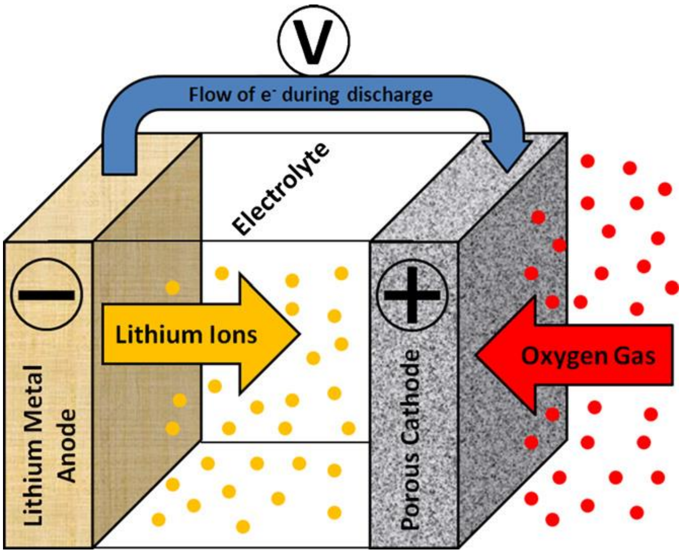


Figure 27 - Schematic of a Li-air battery [22].

During discharge, the lithium ions are conducted from the anode to the cathode through the electrolyte. The electrons are conducted through an external circuit. These lithium ions will connect, at the cathode, to the oxygen reduced with two or four electrons. The reactions that occur during this process are represented below.

$$Li \rightarrow Li^{+} + e^{-} \tag{17}$$

$$2Li^{+} + O_2 + 2e^{-} \rightarrow Li_2O_2 \tag{18}$$

$$4Li^{+} + O_2 + 4e^{-} \rightarrow 2Li_2O \tag{19}$$

Equation 17 refers to the process occurring at the anode. On the cathode, two reactions may occur resulting in the formation of lithium peroxide and/or lithium oxide, (reactions (18) and (19) respectively). The global reaction may be written:

$$2Li + O_2 \rightarrow Li_2O_2 \quad (E^{0} = 2.96V) \tag{20}$$

In the following table, we summarize some advantages and problems that characterize these batteries.

Advantages	Problems
Higher specific energy than other batteries	The battery have to be in a vent site
Safe	
No self-discharge	
Good lifetime	

2.3.2 Redox Flow battery – FB (redox flux)

The redox flow batteries are promising for stationery applications. This technology's may be applied to applications requiring power in the range 10 kW to 10 MW, and can supply energy in the range 500 kWh to 100 MWh. Seven redox pairs are currently being developed (V/V, S/Br_2, Zn/Br_2, V/Br_2, Fe/Cr, Ce/Zn e Pb/Pb), and only three of these technologies are mature enough to be commercialized (vanadium, polysulfide-bromine and zinc-bromine). These three technologies will be developed further on.

These batteries are made up by two electrolyte containing tanks. The anode's side is designated analyte and the cathode's side is designated catholyte. A reservoir designated stack can be found between these two tanks. This is where the reactions between electrolytes that are separated by an ion-exchange membrane (IEM) take place. The electrodes are also located in this reservoir. These three reservoirs are interconnected by conducts and pumps to allow for the electrolyte to circulate. In figure 28 we schematically represent this type of battery.

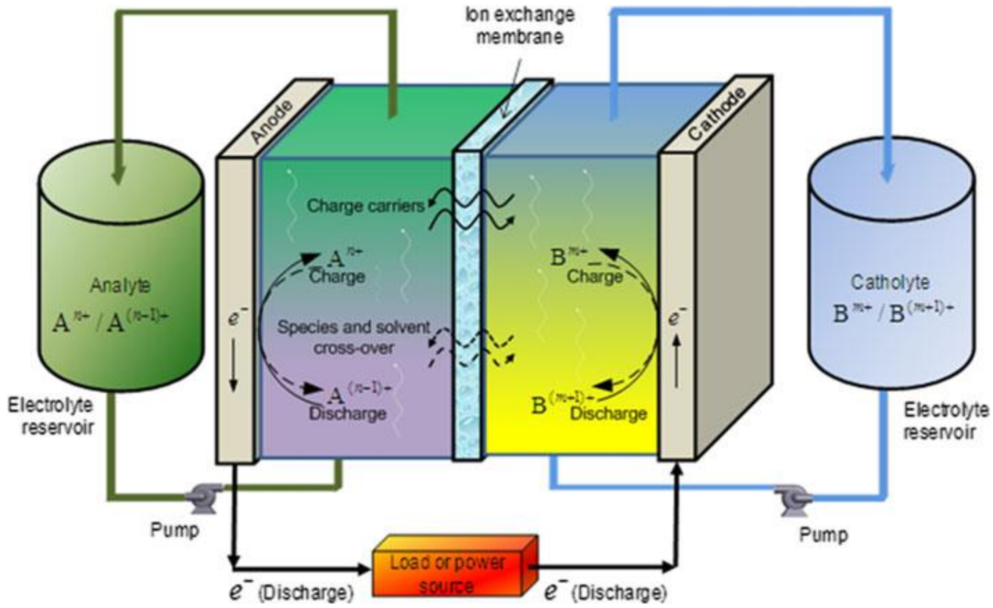


Figure 28- Schematic of a redox flow battery [25].

The electrolyte is constituted by active and solvent chemical species. These active species react, through the following reactions:

$$A^{(n-x)+} \underset{Charge}{\overset{Dischage}{\rightleftarrows}} A^{n+} + xe^- , n > x \tag{21}$$

$$B^{(m+y)+} + ye^- \underset{Charge}{\overset{Dischage}{\rightleftarrows}} B^{m+} \tag{22}$$

During discharge, the anode elevated chemical potential causes an oxidation reaction (21). This results in the liberation of an electron that goes into the external circuit. The electron is then accepted in the cathode and due to the low chemical potential, a reduction reaction occurs (22).

The state of the battery is given by the difference of the chemical potential between analyte and catholyte actives. When the battery is charged, the chemical potential of the analyte is higher than the one of the catholyte. When the battery is discharged, the chemical potential of the analyte is lower than that of the catholyte.

The redox batteries have the ability to separate power from energy. The power is controlled by the stack, while the energy is dependent on the volumes of the electrolyte tanks. The higher the number of cells on the stack (figure 29), the higher the power will be. The power of the cell is the result of the product of the current with the voltage.

The battery’s voltage depends on active chemical species involved in the reactions and on the number of cells that are connected in series. The current is determined by the number of atoms in the active chemical species that react per unit time.

The quantity of energy stored is determined by the total quantity of active chemical species available in a given volume of electrolyte solution in the system.

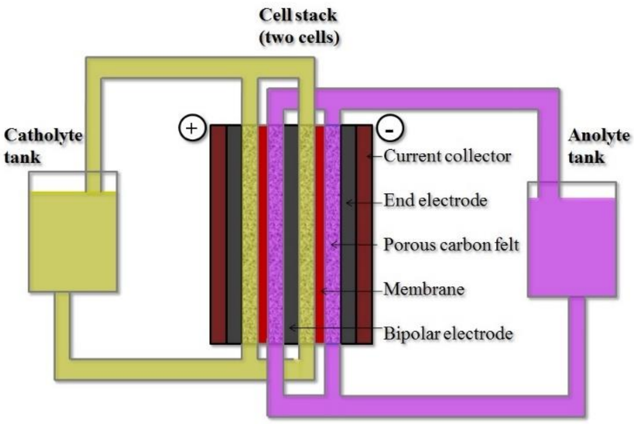


Figure 29- RFB with 2 cells stack [26].

The redox-flow batteries are divided into two categories:

- True redox flow batteries: the active chemical species are totally dissolved in the solution both during charge and discharge. Examples of these kind of batteries are vanadium and iron-chromium batteries.
- Hybrid redox flow batteries: at least one active chemical specie is not dissolved during the charge, which prevents the total separation of power and energy. The zinc-bromine and zinc-chlorine batteries are an examples of these kind of batteries.

2.3.2.1 Vanadium flow batteries (VRB)

Vanadium batteries are very promising in renewable energy applications. This type of batteries use vanadium in both electrolytes as the crossing of active species of two different electrolytes will lead to metal contamination. This results in a loss of efficiency during cycles and consequently a loss in the capacity and degradation of the battery. To prevent this degradation, only one vanadium electrolyte is used in both tanks. In the catholyte, sulfuric acid is used as a supporting electrolyte. In the tanks, the vanadium will be found in four stages of oxidation. In the equations 23, 24, and 25, we present the reactions that occur on the anode, the cathode and the global reaction during the discharge, respectively.

$$V^{2+} \rightarrow V^{3+} + e^- \tag{23}$$

$$VO_2^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O \tag{24}$$

$$V^{2+} + VO_2^+ + 2H^+ \rightarrow V^{3+} + VO^{2+} + H_2O \qquad (E^0 = 1.26V) \tag{25}$$

In Figure 30 it can be seen the schematic and operation of a vanadium battery.

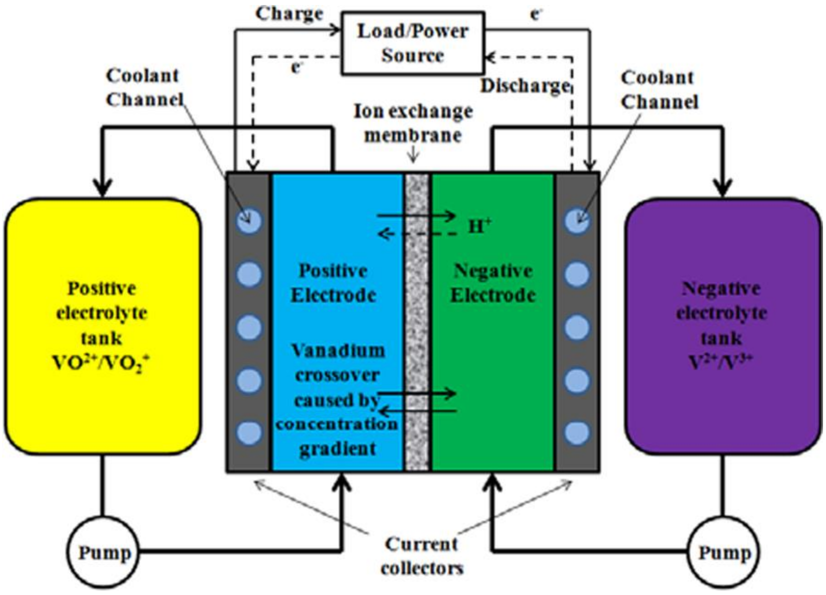


Figure 30- Schematic of a VRB [27].

After several cycles of charge and discharge pH changes. This can lead to a decrease in the efficiency.

The specific energy of the battery is limited by the solubility of the vanadium in the electrolyte, depending on both the temperature and the acid concentration. The ideal work temperature is between 10 and 40ºC. When the system exceeds 40-45ºC, a cooling sub-system is activated. If the battery's temperature reaches 50-60ºC, there is a precipitation of V_2O_5 that is irreversible.

The following table lists the advantages and problems that vanadium batteries may present.

Advantages	Problems
High efficiency	Lower volumetric energy densities specially in high power
Long life and unlimited cycles	High cost of vanadium
Fast charging	Vanadium is toxic
Scales energy and power independently	High cost of maintenance
Fast time answer	
No self-discharge	
Low maintenance	

2.3.2.2 Zinc-bromine flow batteries (ZBB)

The zinc-bromine batteries belong to the hybrid category, therefore, deposition of solid species during charge can occur. This allows for the relationship energy/power to be more permanent than in vanadium batteries.

The electrolyte on the negative side is distilled water based and the electrolyte on the cathode side is an organic amine compound that will maintain bromide captive.

During charge, there will be a deposition of Zinc metal on the anode's surface that will later be dissolved during discharge. On the cathode's surface, the bromide is converted into bromine which is not very soluble in water. However, on the organic amine compound, the bromine reacts and forms a dense and viscous bromine-conduct oil that ends up sinking in the catholyte tank. During discharge, this oil has to mix with the electrolyte in order for the bromine molecule (Br_2) to be reduced into bromide ions (Br). During the reaction, the molecules and the ions may join, forming ions of tribromide (Br_3^-). The discharge reactions on the anode, the cathode and the global reaction are presented in the equations 26, 27 and 28, respectively.

$$Zn \rightarrow Zn^{2+} + 2e^- \tag{26}$$

$$Br_2 + 2e^- \rightarrow 2Br^- \tag{27}$$

$$Zn + Br_2 \rightarrow Zn^{2+} + 2Br^- \quad (E^0 = 1.85V) \tag{28}$$

Figure 31 is a schematic view of a Zinc-bromine battery.

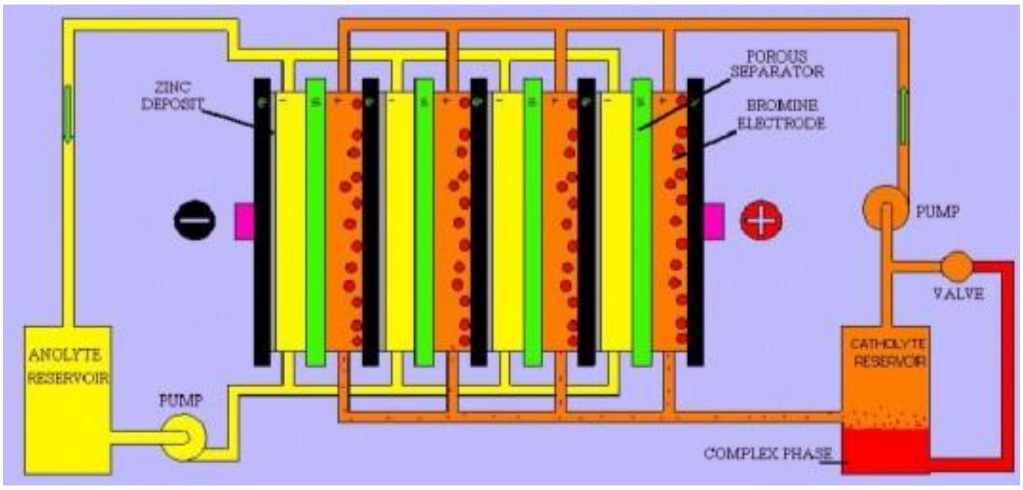


Figure 31- Schematic of a ZBB with 4 cells stacks [28].

These batteries can already be found in the market but continue under investigation in order to obtain better efficiencies and to reduce costs. Within the redox batteries, these are the ones with the best specific energy and release 2 electrons for every zinc molecule. The bromine is, however, highly toxic though inhalation and absorption and also corrosive. This implies that expensive materials need to be used in order to reduce corrosion and prevent dendrite formation. Another issue is the battery's working temperature that needs to be below 45ºC for stable operation. When it reaches 50ºC, the battery either switches off or activates a cooling system, depending on the model. Some advantages and disadvantages of these batteries may be found in the following table.

Advantages	Problems
High specific energy compared with VRB	Material corrosion
Good reversibility	Dendrite formation
Flexible discharge	Electrical shorting
100% DOD	High self-discharge rate
Recyclable	Low energy efficiency
Low weight and easily transportable for FB	Short cycle life
Inherently safe design	Bromine is toxic
	High cost of materials

2.3.2.3 Polysulfide bromine flow batteries (PSB)

Polysulfide-bromine batteries have a certain maturity but are not yet found in the market. In these batteries, the cathode contains sodium bromide and the anode contains sodium polysulfide. The active species are highly soluble which leads to electrolytes with very high specific energy. During the passage of ions through the membrane, precipitation of sulfur species may occur as well as formation of sulfuric acid (H_2S) and bromine (Br_2) [15, 25]. In equation 29, the global reaction of the battery during discharge is presented.

$$2Na_2S_2 + NaBr_3 \rightarrow Na_2S_4 + 3NaBr \quad (E^0 = 1.36V) \tag{29}$$

2.3.3 Hydrogen

Hydrogen (H_2) is the most abundant element in the universe (75%), the lightest, and the one with the highest density (ρ) of energy around 120 kJ/g. The fact that it is quite light, constituted merely by one electron around the nucleus, allows it to have a sufficiently low ionizing strength to remove the electron that orbits in its own nucleus. Through this, we obtain compound ionization and generation of electrical current. One issue that is present in this element is the fact that it is not found in an isolated form in the planet. Due to its low density, it is normally associated to other elements, forming compounds such as water and hydrocarbonates. In NTP conditions, it is a gas that has no smell or flavor and is not toxic.

Hydrogen is not a source of renewable energy, but is a source of storage and energy distribution, that may origin both from on renewable sources or fossil fuels.

H_2 is very versatile since it can be stored in big quantities, and is nonpolluting. During its combustion, there is only release of water vapor and therefore has a very low impact on the environment (depending obviously on the cycle of production, storage, transport, distribution and utilization).

Other than being utilized as fuel, it is also used nowadays by the space industry, chemical industry, petrochemical industry (synthesis of ammonia or methanol, production of iron and steel, treatment of oils and fats), glass industry and electronic component industry. Merely 5% of the produced hydrogen is applied for energetic purposes. A global production of 650 billion of m^3 has been estimated, most of it coming from fossil fuels, having an annual increase of about 10%. The application of hydrogen in fuel cells still represents a very small percentage in the market but has, however, a high growth potential.

One of the best ways to generate energy and fuel for our vehicles, from the emissions point of view, would be a combination of renewable energy and hydrogen. A cleaner and non-fossil future is ambitioned for the automobile industry in order to respond to demands of higher sustainability and a reduction in emissions. This may include vehicles powered by biofuels, electric vehicles and other types powered by fuel cells (FCV).

Renewable energies are, therefore, a desired energy source for the production of this element due to the potential for sustainability that exists in this combination. However, several challenges in producing hydrogen through renewable energies sources are yet to be solved, namely the economic challenge, aiming for it to be a competitive alternative to gasoline and diesel.

Hydrogen may be produced through electrolysis, which utilizes electricity to bring about dissociation of water molecules (H_2O), resulting in oxygen (O_2) and hydrogen (H_2). By continuously providing a current to the cell, the water molecules undergo a reduction on the cell's cathode. The water molecules then separate into hydrogen ions (H^+) and hydroxide ions (OH^-). The separation does not originate neutral elements as oxygen has a higher electronegativity than hydrogen and therefore captures the electron, remaining in its most stable form. The H^+ ion captures an electron from the cathode, giving origin to gaseous hydrogen. The hydroxide ions lose their electrons to the anode and produces gaseous oxygen, verified by the air bubbles in the water. In the following equation, this global reaction is presented.

$$2H_2O \rightarrow O_2 + 2H_2 \tag{30}$$

In figure 32, water electrolysis is represented schematically, taking place in the inside of an electrolyzer.

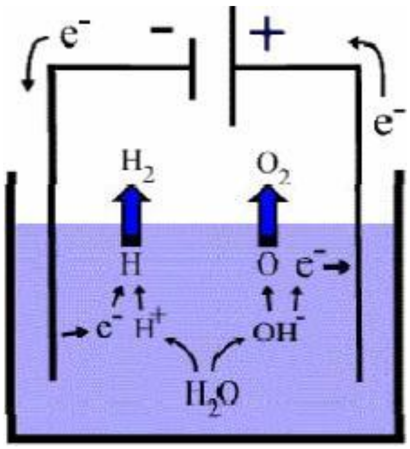


Figure 32- Schematic of the water electrolysis [29].

The efficiency of the electrolytic process lies in the range 70 – 75% and increases with the increase in temperature. This process may still be improved with either the addition of salts to the electrolyte to increase its conductivity or by using vapor electrolysis simply using thermal energy. Its low outcome, when associated to a renewable energy source, is one of the biggest disadvantages found when using this process to produce "renewable hydrogen".

The amount of energy necessary to produce hydrogen is very high and its cost is just as high. Electricity is responsible for two thirds of this energy. For this reason, the production of hydrogen through this process is not, yet, economically competitive and favorable.

The produced hydrogen is then purified and stored in pressurized reservoirs, meaning that the storage is made in the form of chemical energy. Then, this stored hydrogen may be used to once again produce electrical energy through fuel cells. Here, the inverse process of electrolysis occurs.

The working principle of a fuel cell is very similar to that of a battery, although in this case, the source of energy used is hydrogen. The hydrogen is injected onto the anode resulting in a reduction of hydrogen and liberation of electrons into the network. Oxygen is the element injected onto the cathode. The oxygen will react to the hydrogen ions that come from the anode, releasing water vapor during the process. The fuel cells may be associated in series until they have reached the desired voltage. This process is represented in figure 33.

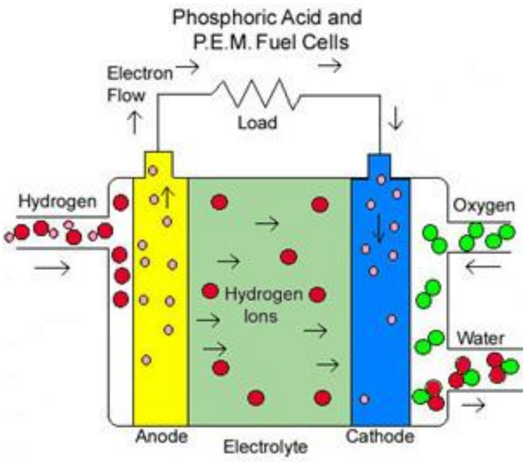


Figure 33- Schematic of a fuel cell [30].

In figure 34, all types of fuel cells that exist are represented, as well as their characteristics.

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Efficiency	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	50-100°C 122-212° typically 80°C	<1kW–100kW	60% transportation 35% stationary	• Backup power • Portable power • Distributed generation • Transporation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194-212°F	10–100 kW	60%	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	150-200°C 302-392°F	400 kW 100 kW module	40%	• Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Pt catalyst • Long start up time • Low current and power
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600-700°C 1112-1292°F	300 kW-3 MW 300 kW module	45-50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	700-1000°C 1202-1832°F	1 kW–2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

Figure 34- Comparison between the different types of fuel cells [31].

2.4 Storage of electromagnetic energy

2.4.1 Superconducting magnetic energy storage (SMES)

Superconductor magnetic energy storage system stores energy in a superconducting coil in the form of a magnetic field. This magnetic field is created by a flow of continuous current (DC) that passes through the coil. For the system to maintain its charge, the coil need to be at low temperatures (-270ºC) because the transition to the superconducting state only occurs at these temperatures. This cooling is achieved with a cryogenic liquid and if this cooling fails, the system ends up suffering stability problems as well as ending up with a very high auto-discharge rate. The discharge of energy is done through the conversion of magnetic energy into electrical energy [3, 16, 32]. The magnetic energy stored in the coil may be calculated using the following formula.

$$E = \frac{1}{2} L I^2 \quad (J) \tag{31}$$

L represents inductance in *Henries* and *I* is the current in *Amperes*. The figure 35 shows a scheme of a SMES system.

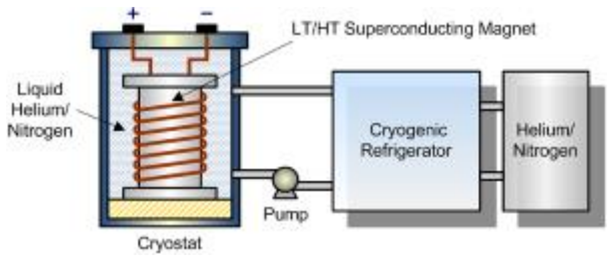


Figure 35- Schematic of a SMES [32].

In the following table, some of the advantages and problems associated to this technology are listed.

Advantages	Problems
High efficiency	High cost of operation
Fast response time	
Near-zero losses	
High power	
Full discharge	

2.4.2 Electric double layer capacitor system (EDLC)

A super capacitor is made by two metal electrodes coated with active coal and separated by a thin porous isolator. The electrolyte may or may not be aqueous, depending on the voltage, on the temperature and on the power or the peak of current necessary. This technology may seem very similar to conventional batteries, except that the super capacitors do not use chemical reactions in their cycles. Instead, they use an electric field between the electrodes [3, 33].

The electrostatic energy stored in the super capacitor may be calculated through the following equation.

$$E = \frac{1}{2} C V^2 \quad (J) \tag{32}$$

C represents capacitance and V represents the difference in voltage between the plates of the capacitor. An EDLC is represented in the figure 36.

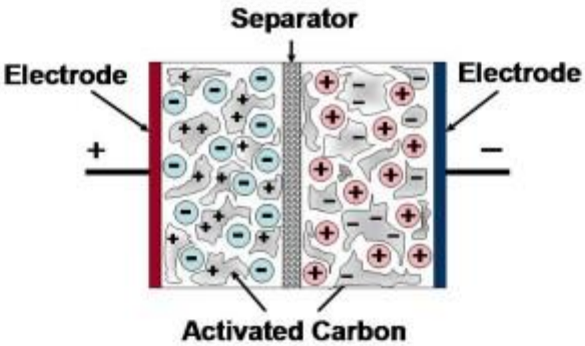


Figure 36- Schematic of an EDLC [33].

The following table lists some advantages and problems of this technology.

Advantages	Problems
High charge/discharge rates	High self-discharge
High power density	Need complex electronic control
High efficiency	Low specific energy
High lifetime	

3. Overview

Each storage technology presents different characteristics which allow them to be different from one another and more suited for each type of application.

An analysis and comparison of some characteristics of different technologies will be done shortly. It is necessary to be aware that some of these technologies are still under research and all their characteristics are therefore not yet available.

In Figure 37, we represent the costs per kilowatt (kW) for each type of storage technology.

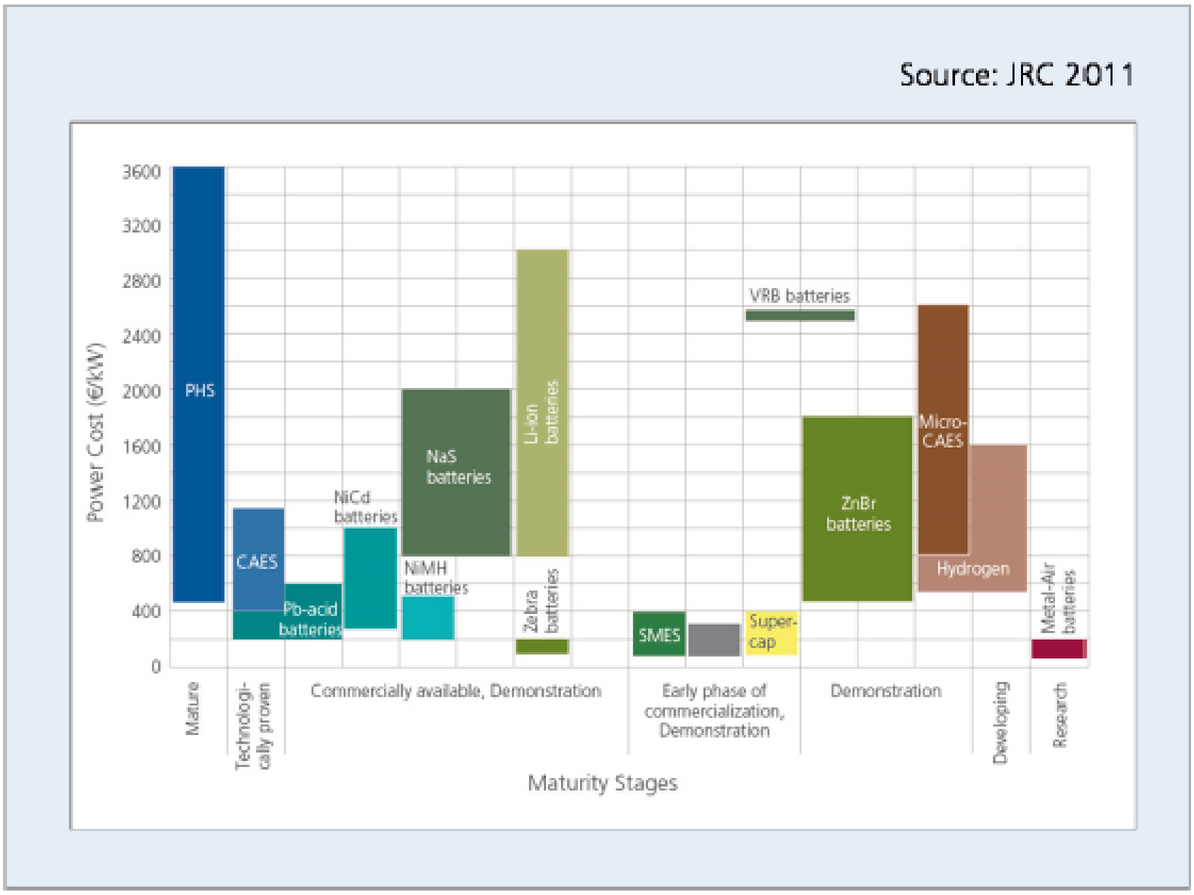


Figure 37- Power cost of storage technologies [43].

The technologies that present the highest cost per kilowatt are *PHS*, the *Li-ion*, flow batteries (*VRB* and *ZBB*) and *micro-CAES*. The cheapest technologies are *lead acid batteries*, *nickel and metal hydride batteries*, *SBB*, *SMES*, *EDLC* and metal-air batteries. It is, however, necessary to keep in mind the maturity of the technologies, and take into account that some of them are still not available in the market and still under investigation. For this reason, the presented values are simply potential values and not real ones.

As previously mentioned, different technologies suite better different kind of applications. Some of the relevant characteristics that help the choice of technology for a particular application are is its rating power, its discharge time and its self-discharge. In the following table these characteristics are presented for different technologies[1].

[1] The table with all characteristics is shown on the annex A (table 14).

Table 1 - Power rating, discharge time and self-discharge for storage technologies [14,16].

Technology		Power rating	Discharge time	Self-discharge per day
PHS		100-5000 MW	1-24 h+	very small
Flywheels		0-1 MW	Milliseconds-15 min	100%
CAES		5-400 MW	1-24 h+	small
Secondary batteries	Lead-acid	0-20 MW	Seconds-hours	0.1-0.3%
	NiCd	0-40 MW		0.2-0.6%
	NiMH			0.3%
	SBB	50 kW-8 MW		~20%
	L-ion	0-100 kW	Minutes-hours	0.1-0.3%
	Li-S			0.3-0.5%
	Li-air		Seconds-24 h+	very small
	Zinc-air			
Flow batteries	VRB	30 kW-3 MW	Seconds-hours	small
	ZBB	50 kW-2 MW		
	PSB			
Fuel Cells		0-50 MW	Seconds-24 h+	almost zero
SMES		100 kW-10 MW	milliseconds-8 s	10-15%
EDLC		0-300 kW	milliseconds-60 min	20-40%

PHS and *CAES* are the kind of technologies that are adequate for storing large quantities of energy for a long period of time. This is due to the low losses in energy per day.

The *flywheels*, *SMES* and *EDLC* are technologies that are more indicated in obtaining extra energy for a short period of time. In other words, they are able to store energy for a short period of time and are then able to discharge that energy in a short time. These technologies are most suited for grid quality control applications.

Fuel cells and batteries are the kind of storage mostly used in diverse applications. This is due to their ability to store energy for a long period of time and their ability to discharge that stored energy during a few hours or even days. The secondary batteries present a higher rate of auto-discharge comparatively to flow batteries and to fuel cells. However, as shown in figure 37, they also present a lower cost, making them more favorable to the market.

Through this analysis we are able to confirm that, so far, batteries are the technology most suitable for the application to a photovoltaic hybrid system. A deeper analysis of the different types of batteries will shortly be made.

In figure 38, specific energies for each battery type are shown.

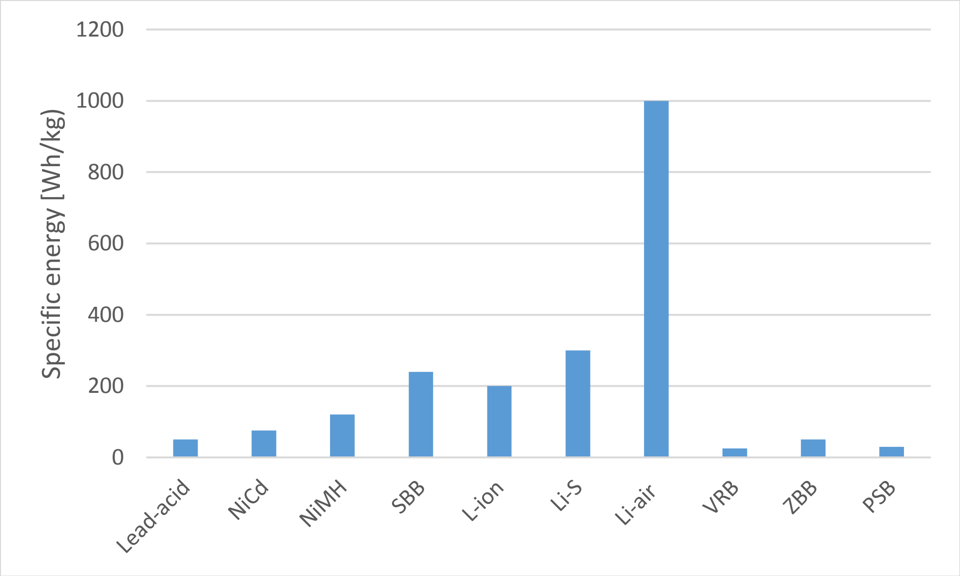


Figure 38- Batteries specific energy.

As previously mentioned, the specific energy of a battery is a very important parameter, since the higher the specific energy, the higher the capacity of the battery.

The *lithium batteries* present a higher specific energy, making them more suitable for applications in transports and portable applications. *Sodium-Beta Alumina batteries* also present a high specific energy in relation to the remaining batteries. This technology however, is not yet completely developed (figure 37) and presents a very high auto-discharge (table 1).

In the following figure, the lifetime of the various batteries are represented.

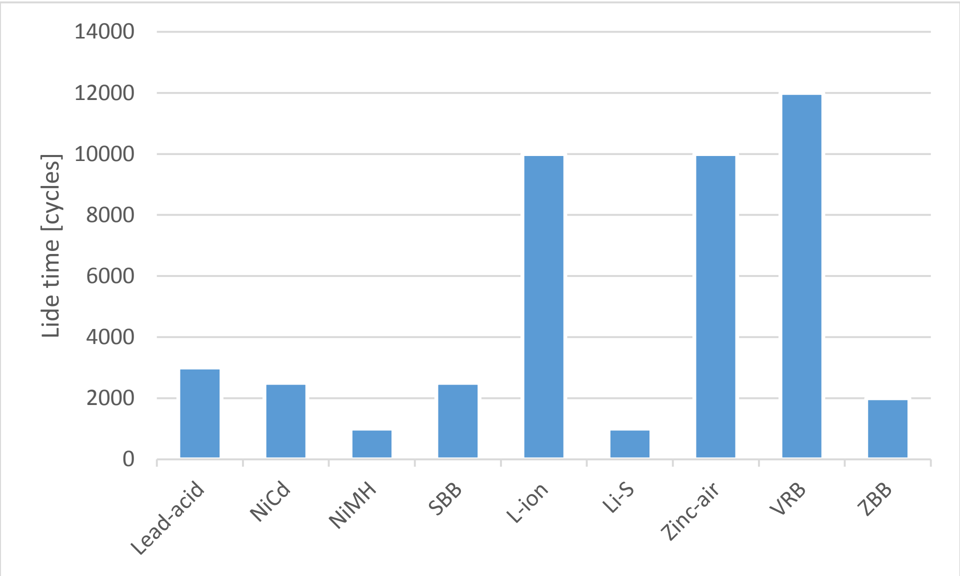


Figure 39- Batteries life cycle.

The batteries that present a higher lifetime are the *vanadium flow*, the *zinc-air* and the *Li-ion batteries*. The *lithium-sulfur batteries* and the *Ni-MH batteries* present a very reduced lifetime in comparison to the remaining batteries.

In the following figure, the cost of energy per cycle is shown.

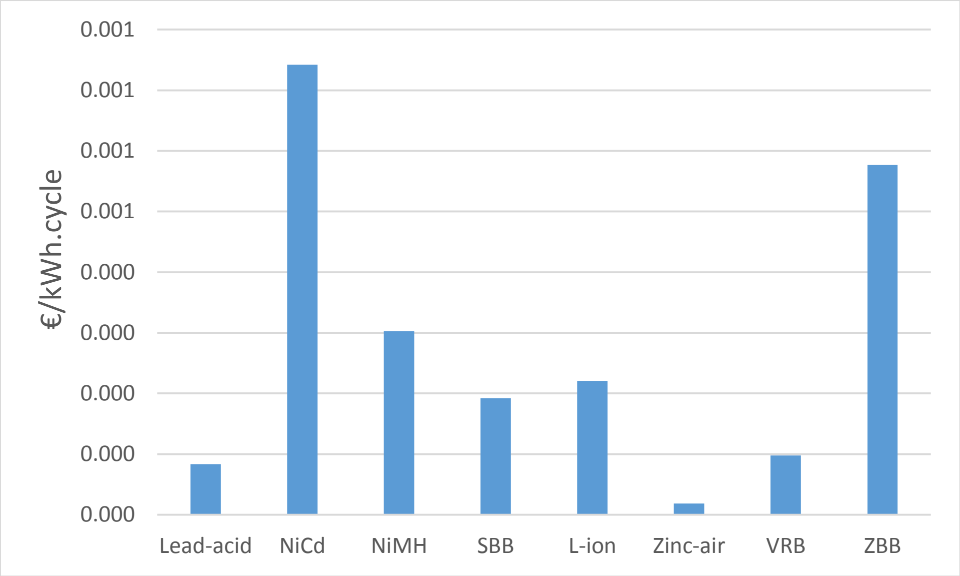


Figure 40 - Batteries capital cost per cycle.

The batteries that exhibit a higher cost per cycle are the *nickel-cadmium* and the *ZBB batteries*. *Zinc-air batteries* present the lower costs but since they are still in development, they cannot yet be found in the market.

Despite the high cost of the *vanadium batteries*, they present a DOD of 100% and a very high lifetime (fig. 39). This allows the cost per cycle to be very low. The *lead acid batteries* also present a low cost per cycle in comparison to other technologies. This is due to their low initial cost and their high number of cycles.

Following this analysis we must conclude that, for the moment, the most suitable batteries for PV systems are the *lead acid* and the *vanadium flow batteries*.

4. Applications

4.1 Applications for distributed energy storage

Stored energy can only be distributed in a chemical form. Thus, is may be distributed in batteries and in the form of hydrogen. As previously mentioned, hydrogen can be compressed and stored in carbon fiber tanks, allowing for its transportation. Another way of distributing hydrogen is through a pipeline network.

4.2 Industrial and commercial applications

To analyses storage impact on commercial and industrial applications, it is necessary to take into account the consumption daily profile that we are targeting because this daily profile may change a lot depending on the type of application. We can consider that the peak consumption for commercial and service buildings happens between 9h and 19h. In the industry however, the peak consumption may change, depending on the type of industry. Some may work 24 hours during 7 days a week and others may have a 9h till 18h schedule, 5 times a week. In figure 41, we represent an example of the demand for each of these types of application.

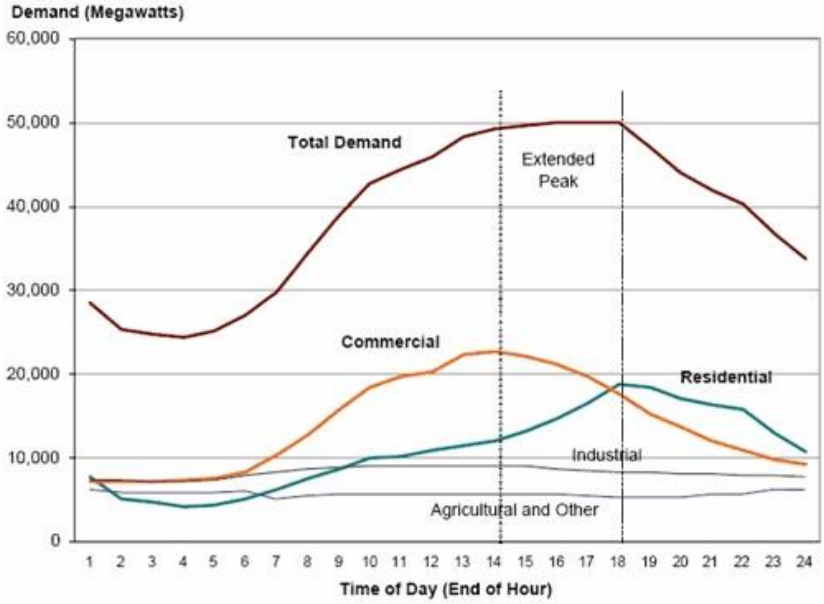


Figure 41- Demand [36].

For the system to be autonomous, it is necessary for the hybrid system (PV + batteries) with a diesel generator in backup. In the case of an industrial application, contracted power of 100 kW was considered. This power would be continuous throughout 24 hours, for an industry that operates during night, or for an industry operating from 9h to 18h, with a residual consumption of about 6 kW. The residual consumption includes the building’s air-treatment and air-conditioning systems and some equipment that remains working during the night.

For a commercial application, a contracted power of 20 kW was considered with a 7 kW residual consumption during the night. The figure below illustrates the evolution in consumption for different applications throughout the day and the solar irradiation during the month of December, in a typical year, in Oliveira de Frades.

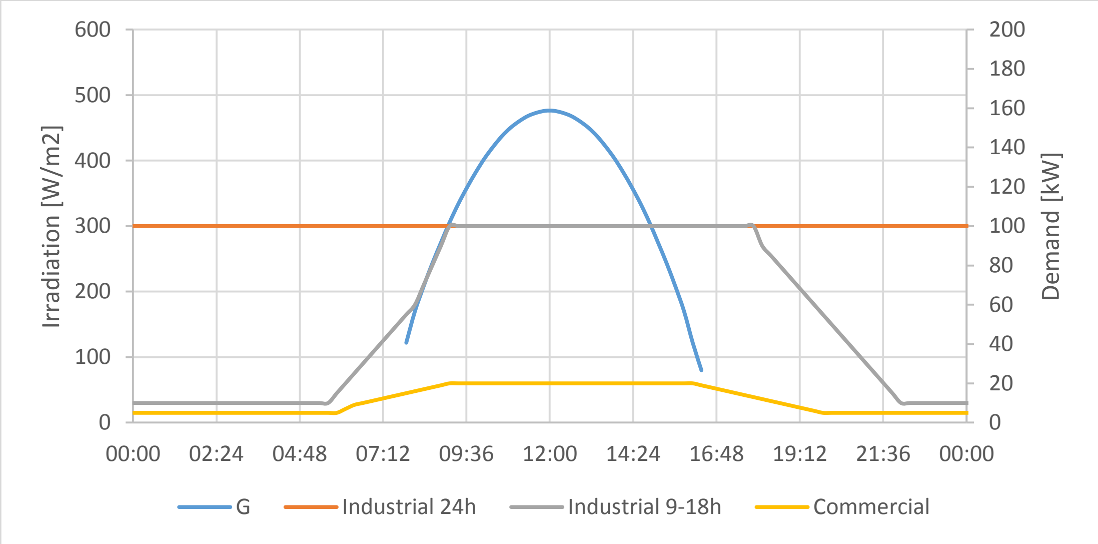


Figure 42- Industrial and commercial demand and irradiation for a typical December day.

For the case of an industry with continuous working hours, the ideal would be to have a hybrid system where a direct consumption of energy would occur, from photovoltaic panels that would provide at the same time, battery storage. During the night, the batteries would be discharged between 16h and 24h. During low-peak hours (0h to 7h), it would be best to use the grid, since in this period, energy would be cheaper.

Figure 43 illustrates the evolution in consumption for an industry with working hours from 8h till 18h.

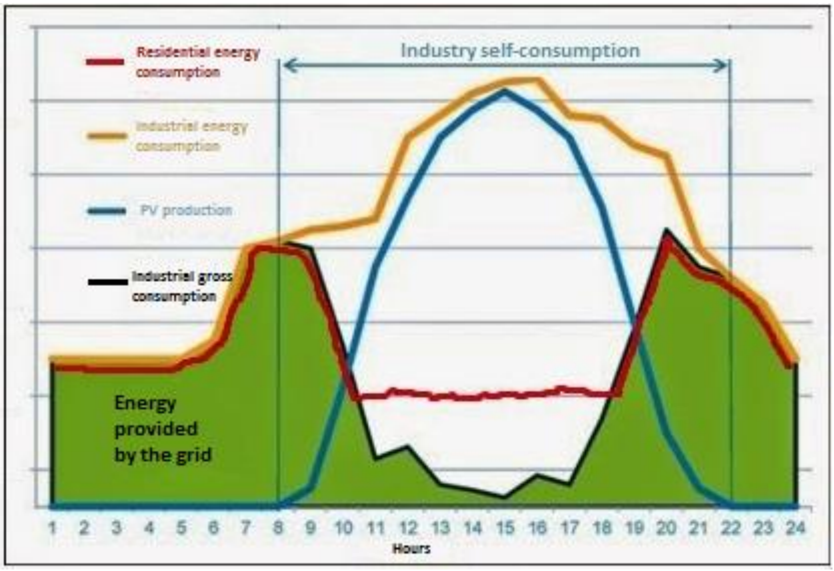


Figure 43- Industrial consumption [37].

As observed in Figure 43, the use of a PV system could reduce considerably an electricity bill. During peak hours, the energy produced can be used directly, allowing for a reduced consumption of the energy from the grid. Apart from the auto-consumption, it is also possible to store energy produced by the PV system in batteries. This energy would be consumed later on when the production of renewable energy did not meet consumption requirements. Another option would be to recharge batteries during low-peak hours, when energy is cheapest, and then use this energy when consumption is higher than production. This way, it would be possible to avoid using energy from the grid, which is normally more expensive during peak hours. This type of industrial consumption is very similar to commercial consumption, meaning that the same options for storing energy may be applied.

4.3 Residential applications

Residential consumption has a variety of variations throughout the day. Normally, two peaks of consumption are present, one in the morning from 6-8h and another at night around 20h. These peaks are mostly due to the population’s working period. For a better consumption management, apart from the energy provided from the grid, a hybrid system can be implemented.

Figure 44 demonstrates the variation in consumption, and the expected production of renewable energy from a PV hybrid system and how its consumption can be managed. This example is based on a small contracted power of 1kW just for convenience.

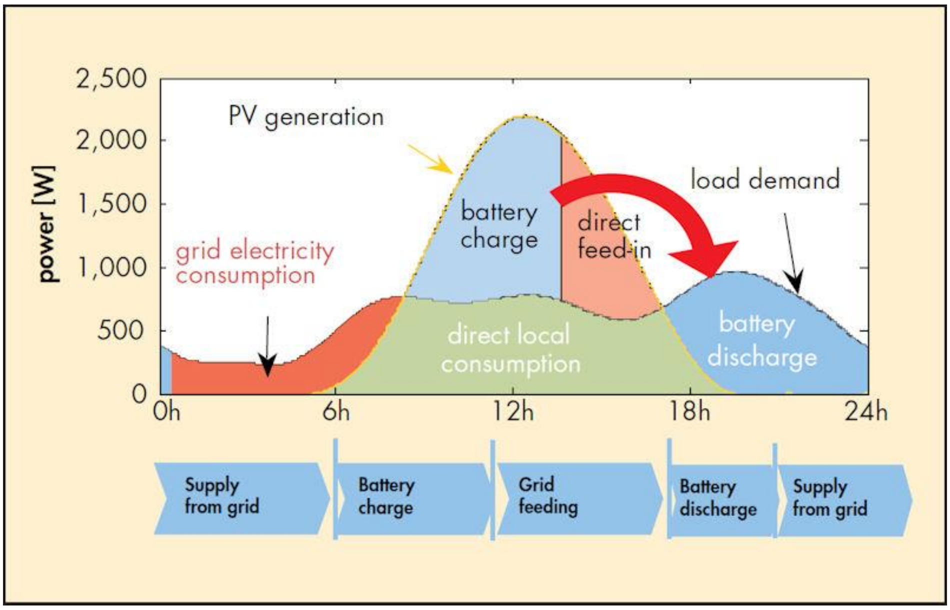


Figure 44- Residential demand [38].

Due to the variability of consumption in the residential sector, with the lowest consumption being at midday, a PV system would allow for storing energy during those hours, and then use it in peak hours, between 18h and 24h. This way, the consumer would only be using energy from the grid during low-peak hours, which is cheaper. During peak-hours, energy would be injected into the grid from the photovoltaic system, a period during which energy is more expensive.

Figure 40 demonstrates the variation on demand using only a PV system and a hybrid system.

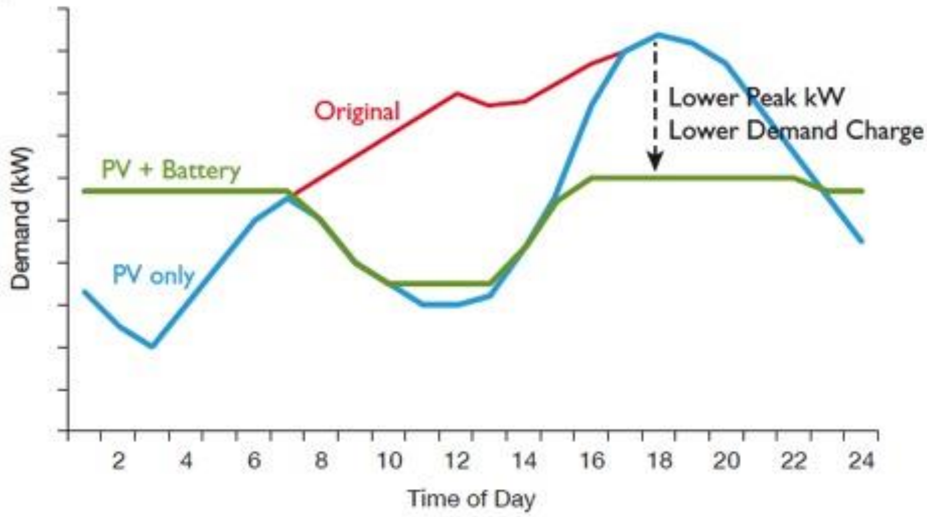


Figure 45- Residential demand with PV system and batteries [39].

Through the analysis of the figure, we can conclude that the demand of energy can decrease considerably with a hybrid system. This happens since the energy stored during sunlight hours, is later used during peak-hours.

4.4 Applications for transports

For transports, batteries and hydrogen can be used as storage technologies. Batteries may be used in plug-in cars, which can be recharged during the night when electricity is cheaper or at electric service stations throughout the city. These batteries need to have certain characteristics to be used in vehicles, such as high specific energy, high autonomy and safety. Lithium batteries are the most used for this kind of application since they present the highest specific energy within the secondary batteries. They also present, however, low autonomy and high risk of explosion. One of the technologies still in development, and presenting very promising characteristics for this type of application, is the Li-air batteries. These have the higher specific energy in the lithium batteries (figure 46), making their autonomy higher and they do not present risk of explosion.

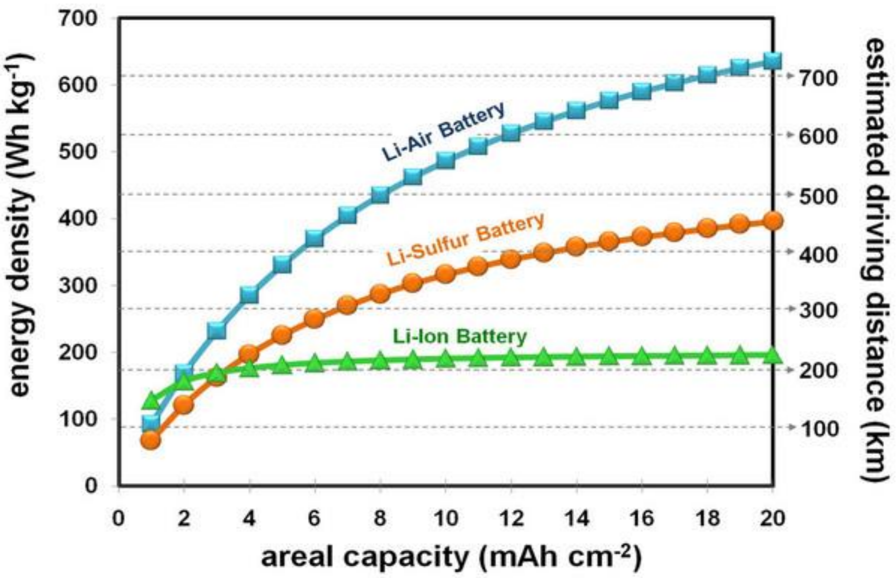


Figure 46- Energy density for different types of lithium batteries [40].

There are vehicles that use hydrogen as a combustion fuel, which is converted into electricity through fuel cells.

As referred to previously, hydrogen can be produced through electrolysis, using electricity from renewable sources, such as the wind power. This renewable source has its production peak during the night, when demand is reduced. This means that the energy produced in wind parks can be used to produce hydrogen. The hydrogen will then be stored in tanks and commercialized in service stations to supply fuel cell vehicles.

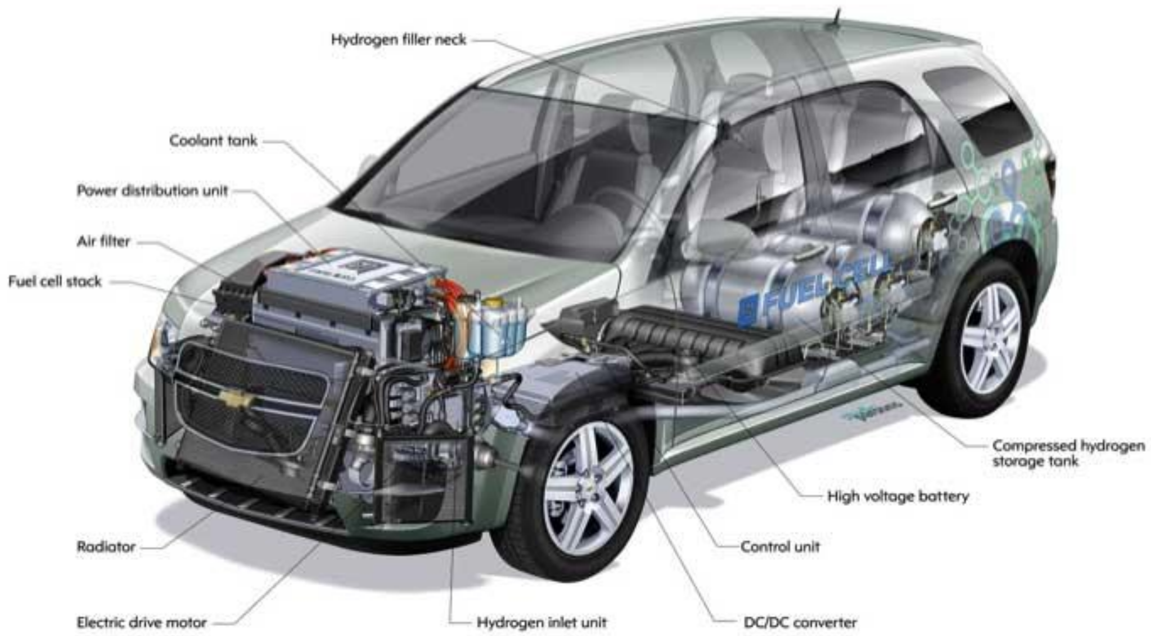


Figure 47- Fuel cell car [41].

4.5 Off-grid applications

In off-grid applications, it is possible to use a source of renewable energy, such as a PV panel with energy storage (batteries) and a diesel generator as backup. The PV system will produce electricity during the day for auto-consumption and will store energy in the batteries to.

As this is an off-grid application, the sizing of the batteries bank must be made with autonomy for several days, because it is not possible to use the grid when there is not enough sun during several days. When battery's autonomy is not sufficient, it is possible to use the generator to produce extra energy. In figure 48, an example of an off-grip application with a hybrid system and a diesel generator is shown.

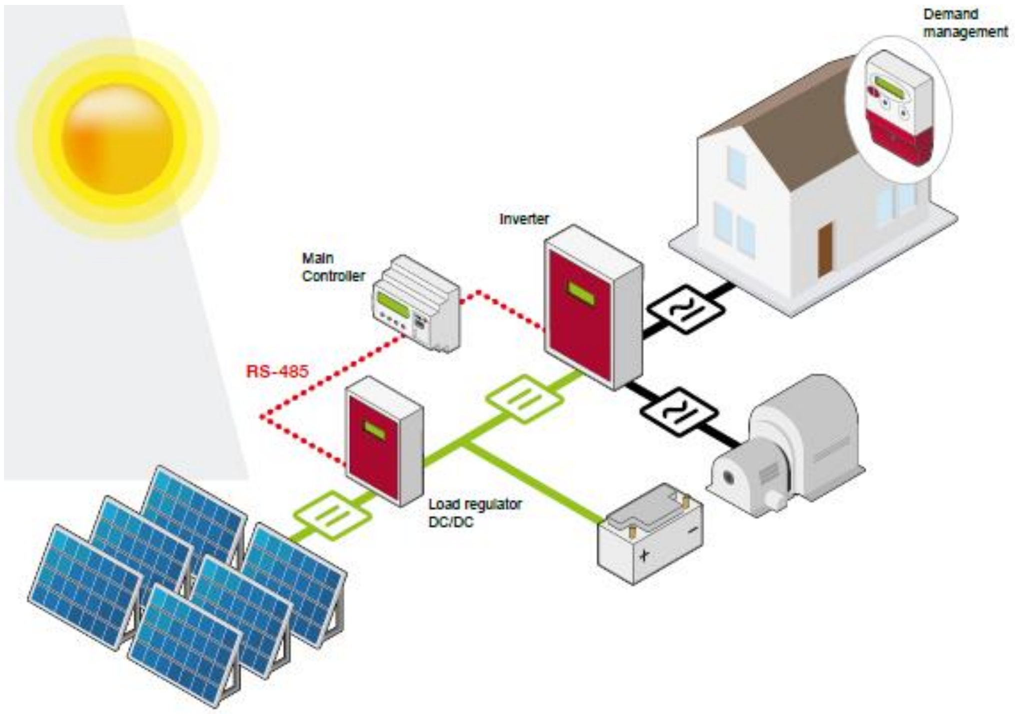


Figure 48- Off-grid application [42].

In off-grid applications, the system requires intelligent networks for consumption management. In other words, the consumptions should always be inferior or equal to production. When it is superior, it needs to resort to the batteries or the generator to supplement that necessity. When the production of renewable energy is higher than demand, the extra energy will be stored in the batteries to later be used when there is no production. The system is controlled by two devices that manage the consumption and the production. The *Main Controller* controls the production and the *Demand Management* controls the consumption.

4.6 Applications for integration with renewable resources

Since renewable energy is variable and not controllable, energy production will in general not match demand. A way of avoiding this problem is to store energy when it is produced and not needed. The wind power plants are an example of this process since their peak production is usually during the night when consumption is low. To not shut down the centrals, the energy produced may be used, for instance, for pumping water in PHS. This means that during the night, the water is transported from the downstream dam to the upstream dam, to be used later, when necessary. This is a good form of storage since the cost for producing electricity in PHS is significantly lower compared to other forms of storage technologies (figure 49). Another advantage comes from the fact that hydroelectric centrals are dispatchable and, when necessary, can produce electricity to meet demand very fast.

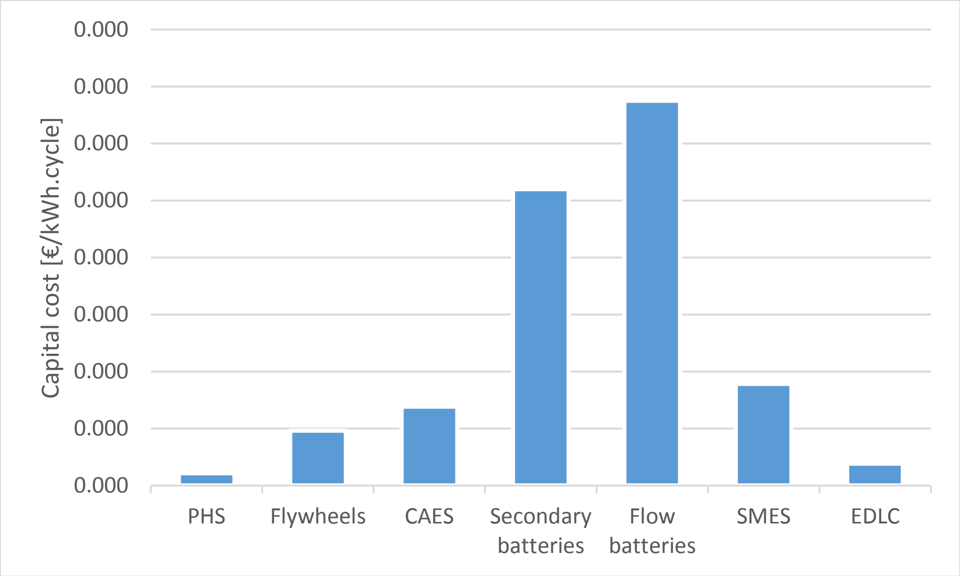


Figure 49- Capital cost per cycle for different technologies.

5. Markets

5.1 Current markets

Energy storage projects have been increasing in the past few years. This increase is due to the search for storing capacity by companies and particulars. However, the cost of these technologies continues to be high, and in the current economic context, companies find it difficult to invest without governmental support.

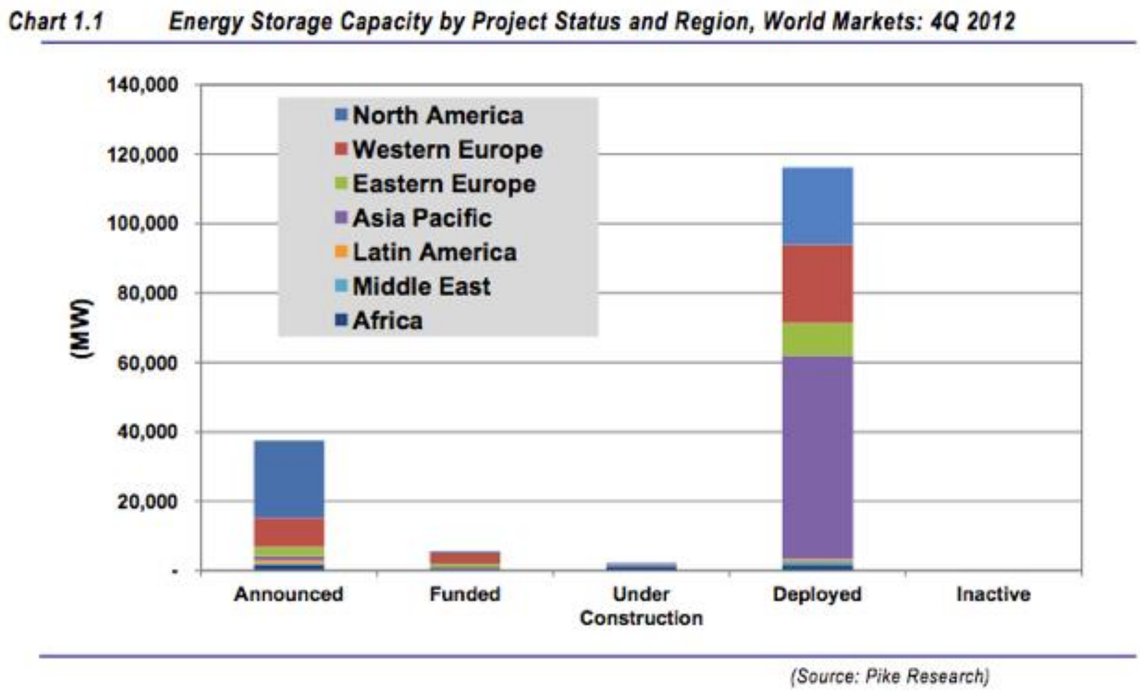


Figure 50- Energy storage capacity by project status and region [44].

By analyzing figure 50, Asia Pacific leads the market in terms of deployed projects on energy storage. They are followed by Europe and then by North America. North America has many new projects announced, reflecting their innovation in this field. Europe also presents some storage capacity in announced projects, in connection with the implementation of renewable energies.

PHS is the storage technology with more installed power throughout the world and with potential to growth in the future. Even though it needs large infrastructures and a high initial cost (figure 49), this technology continues to be preferred. For smaller scale applications, the chosen technology is the battery since it presents a very high specific energy value and its price has been decreasing throughout time.

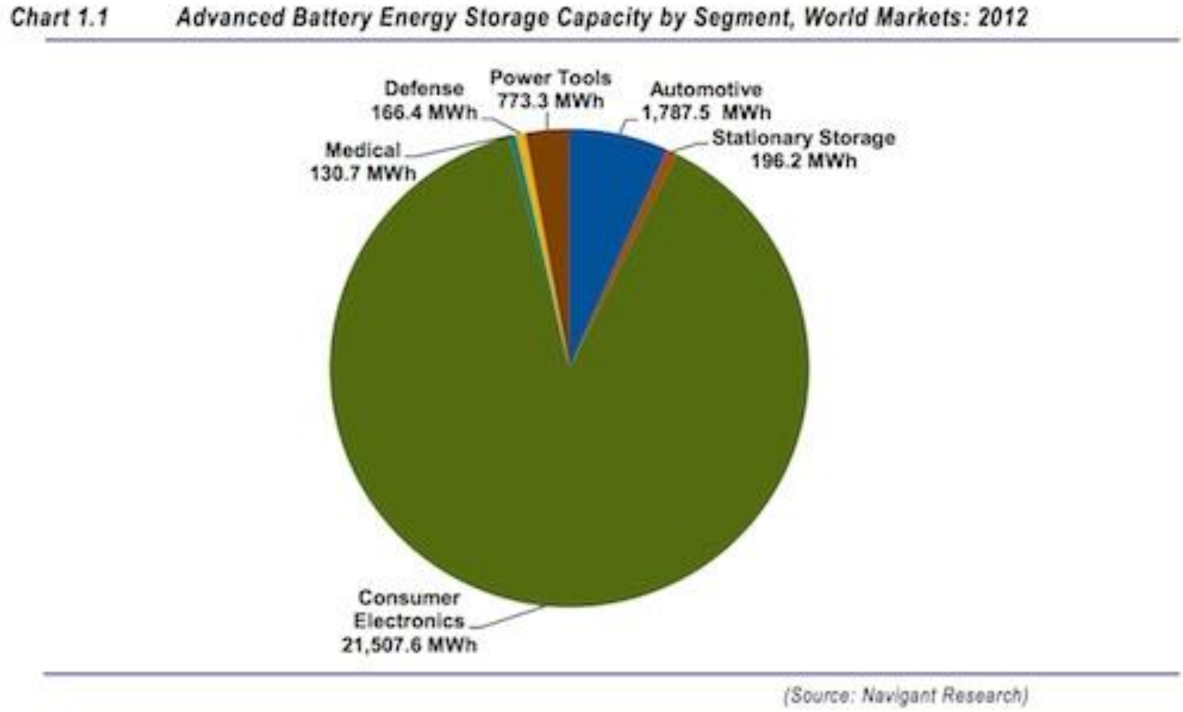


Figure 51- Advanced battery energy storage by segment, World Markets: 2012 [45].

In figure 51, the battery market is represented. It is possible to observe that more than 87% of the market belongs to the electronic consumables. The vehicle section represents a small percentage in the battery market. However, this value may begin to increase due to the implementation of electric vehicles in the market. Stationary storage represents just 0.8% of the total, making this segment, one of big potential and opportunity in the market.

5.2 Opportunities

The market opportunities are found in three zones: in the north of North America (Canada and north of United States of America), in Europe and in non-developed countries (Asia Pacific, Africa and Latin America)

One of the very important market segments, are for the commercial building to have an uninterrupted power system (UPS), betting this way, on a system for energy storage. Figure 52 shows a prediction of this market's growth.

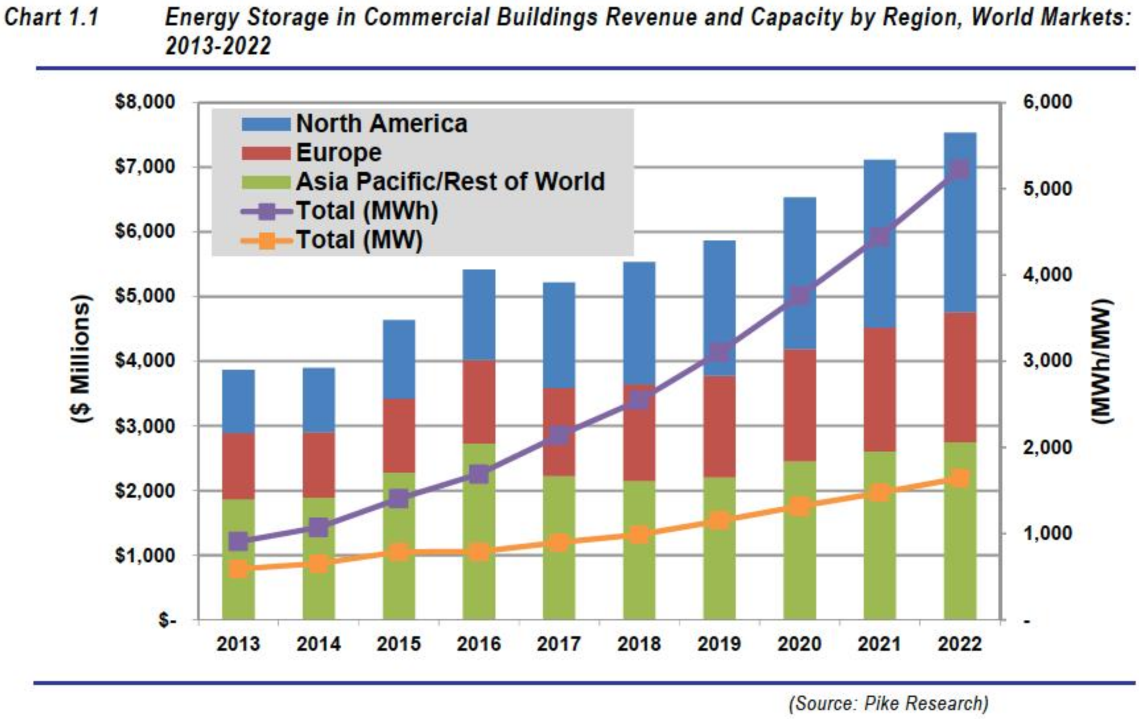


Figure 52 - Energy storage in commercial buildings revenue and capacity by region [45].

The tendency of a market for energy storage, in the segment of commercial buildings, is to increase over the years, especially in North America, Europe and Asia Pacific. The capacity may increase five times more and the installed power may double within nine years.

The biggest opportunity in the European market is in the auto-consumption segment. This is because what defines Europe is the integration of renewable energies and as already mentioned, the renewable energies must rely on storage. In the different sections, PV systems can be installed to produce energy during peak hours, when electricity is more expensive. By implementing the auto-consumption, the energy produced may be used directly and the remainder is stored to use later on, as mentioned earlier in the “Applications” chapter.

In the north of North America, there are many adverse situations that cause breakdowns on the grid during several days. For this reason, systems to store energy may be implemented to stabilize transmission and energy distribution (T&D).

Countries like India, Mexico, Peru, Chile and most countries in the African continent, do not have a very complete T&D network. This results in many villages, and isolated places not having electricity and creates, therefore, opportunities in the market for off-grid applications.

6. Case study: Integrating PV system – storage

6.1 Characterization of the system

A case study was made for three different applications: an off-grid hybrid system, a hybrid system connected to the grid and an off-grid hybrid system with a diesel generator. It was taken into consideration that all three were located in Oliveira de Frades, Portugal. Radiation data was obtained using PVGIS, and a total of 3.22 peak hours were obtained per day for the month of December. It was also considered that the efficiencies of the inverter and of the cables are of 90% and 95% respectively.

For the off-grid application, a PV hybrid system of 10 kWp with battery was considered. It is loaded with a demand of 2.25 kW, during 9h, making the building's consumption 20.25 kWh per day. The system was considered to have two days of autonomy, working at 48 V DC.

For the application connected to the grid, a PV hybrid system of 200 kWp was considered. It is loaded with a demand of 45.45 kW, during 9h, giving it a daily consumption of 409.05 kWh. For this system, it was also considered to have two days of autonomy, working at 48 V DC.

For the third case, a PV hybrid system of 2 MWp was considered, assisted of a diesel generator. It is loaded with a demand of 454.85 kW, during 9h, corresponding to a daily consumption of 4093.65 kWh. For this system, only one day of autonomy, working at a voltage of 400 V DC, was considered.

6.2 Choice of storage technology

As referred to in the Chapter "Overview", the most suitable technology for this kind of application are the *lead acid* batteries and the *vanadium flow* batteries. A few batteries of different name brands and with different characteristics were chosen to make a comparison. The following table shows the different batteries that were chosen.

Table 2- Batteries.

Type	Model	Supplier	Reference
FLA	Exide classic	GNB Industrial power	OPzS solar 4600
VRLA	ABSOLYTE GP Stackable		1-100G99
	Sonnenschein A600 Solar		A602/3920 Solar
	Sonnenschein Solar		S12/230A
VRB	CellCube	Gildemeister energy solutions	FB 10
ZBB	Redflow ZBM	RedFlow advanced energy storage	

The *Exide Classic* battery is a lead-acid flooded battery that will require some maintenance throughout time. The remaining lead-acid batteries do not require maintenance since they are valve-regulated lead-acid. The *ABSOLYTE GP* battery is an AGM battery and the *Sonnenschein* batteries are gel batteries[2].

[2] The batteries datasheet are in the annex B.

These lead-acid batteries are more commercialized, making their price much lower in comparison to the redox-flow batteries. The price of the *Redflow ZBM* battery was not found and will therefore be excluded in the following tables. Its characteristics will however be found attached.

Table 3- Batteries characteristics.

Battery	Storage capacity [Ah]	Voltage [V]	Battery price	Cost [€/kWh]	Lifetime [cycles]	DOD [%]	Operational costs [€/kWh.cycles]
OPzS solar 4600	4600	2	1 240.00 €	134.78 €	3000	60	0.07
1-100G99	6300	2	2 178.34 €	172.88 €	1200	80	0.18
A602/3920 Solar	3919	2	1 220.00 €	155.65 €	3000	60	0.09
S12/230A	230	12	375.00 €	135.87 €	800	60	0.28
FB 10	2083	48	100 000.00 €	1 000.00 €		100	

Through analysis of table 3, it is possible to observe that the *Sonnenschein Solar* battery "*S12/230A*" is the one presenting the lowest capital cost. Its capacity and life time, however, are smaller compared to the remaining lead-acid batteries. The *OPzS solar 4600* battery presents the lowest cost per cycle due to its long life time. This battery however, requires maintenance, unlike the remaining batteries. This may become a problem when a system contains a high number of batteries.

The *CellCube* battery has almost unlimited life cycles making its cost per cycle very reduced. However, its initial cost is very high in comparison to the other technologies, making this option unfeasible.

Next, a sizing for each case study will be done to verify which battery is more suitable for each case.

6.3 Sizing

6.3.1 10 kWp PV system

For the sizing to be completed, it is necessary to know the daily consumption, the system's autonomy, the losses in the inverter and the cables, and the DC voltage. Since what matters is the sizing of the energy storage, losses in the photovoltaic system and the charge controller will be ignored.

The battery's capacity will depend on the desired depth of discharge. Since not all batteries have the same DOD, the nominal capacity required for the system will first be calculated, using the following expression:

$$C_N = \frac{Demand \times Autonomy}{V_{DC}(\eta_{inv} \times \eta_{cab})} \quad [Ah] \tag{33}$$

The following table shows the characteristics of an off-grid PV hybrid system.

Table 4 - 10 kWp system characteristics.

System power [kWp]	10
Demand [kWh]	20.25
Autonomy [days]	2
System voltage [V]	48
DC load [Wh]	47368
Nominal capacity [Ah]	987

Once the nominal capacity of the storage is known, it is possible to know the nominal capacity for each type of battery. This can be done by dividing the system's nominal capacity by the battery's depth of discharge. In the case of the *CellCube* battery, it is also necessary to divide by the battery's efficiency value.

The following step is to know the number of strings (34) and the number of batteries in parallel (35) in order to know the total number of batteries of the batteries bank.

$$N_s = \frac{V_{DC}}{V_B} \tag{34}$$

$$N_p = \frac{C_N}{C_B} \tag{35}$$

Table 5 - Batteries characteristics for 10 kWp system.

Model	Capacity [Ah]	Voltage [V]	DOD	Efficiency	C_N [Ah]	Ns	Np	Total
OPzS solar 4600	4600	2	70%		1410	24	1	24
ABSOLYTE GP Stackable	6300	2	70%		1410	24	1	24
Sonnenschein A600 Solar	3919	2	70%		1410	24	1	24
Sonnenschein Solar	230	12	70%		1410	4	7	28
CellCube	2083	48	100%	80%	1234	1	1	1

As foreseen, if the *Sonnenschein Solar* battery is utilized, the bank of batteries will contain 28 batteries, an extra 4 batteries in comparison to the other lead-acid batteries. The *CellCube* batteries have a higher capacity than required, making only one module necessary.

For the choice of the best battery to be made, it is necessary to know the total cost for the bank of batteries as well as the cost per cycle.

Table 6 - Batteries cost for 10 kWp system.

Model	Batteries total	Unit price	Total price	Cost per cycle
OPzS solar 4600	24	1 240.00 €	29 760.00 €	9.92 €
ABSOLYTE GP Stackable	24	2 178.34 €	52 280.25 €	43.57 €
Sonnenschein A600 Solar	24	1 220.00 €	29 280.00 €	9.76 €
Sonnenschein Solar	28	375.00 €	10 500.00 €	13.13 €
CellCube	1	100 000.00 €	100 000.00 €	

The bank of batteries containing *Sonnenschein Solar* batteries, contains a higher number of batteries but the total cost remains inferior to the remainder. The cost per cycle, however, is higher than the *Sonnenschein A600 Solar* batteries. The difference between the cost per cycle is lower in comparison to the difference between the final cost of the batteries. This therefore makes the *Sonnenschein Solar* batteries the final choice of battery, presenting an initial cost of 10 500.00 € and a bank with 28 batteries.

6.3.2 200 kWp PV system

As referred to previously, this application consists in a PV hybrid system connected to the grid. It may be considered that this system targets the auto-consumption market mentioned in Chapter 5 and may work as a residential application, referred to in chapter 4.3.

By using expression 33, it is possible to calculate the system’s nominal capacity, presented in table 7.

Table 7 - 200 kWp system characteristics.

System power [kWp]	200
Demand [kWh]	409.05
Autonomy [days]	2
System voltage [V]	48
DC load [kWh]	956.84
Nominal capacity [kAh]	19.93

With a nominal capacity of 19.93 kAh, it is possible to calculate the number of strings and batteries in parallel, using expression 34 and 35 respectively.

Table 8 - Batteries characteristics for 200 kWp system.

Model	Capacity [Ah]	Voltage [V]	DOD	Efficiency	C_N [Ah]	Ns	Np	Total
OPzS solar 4600	4600	2	70%		28477	24	7	168
ABSOLYTE GP Stackable	6300	2	70%		28477	24	5	120
Sonnenschein A600 Solar	3919	2	70%		28477	24	8	192
Sonnenschein Solar	230	12	70%		28477	4	124	496
CellCube	2083	48	100%	80%	24918	1	12	12

When using the *ABSOLYTE GP Stackable* batteries, the bank merely needs 120 batteries to obtain the desired capacity.

Table 9 shows the cost of the battery bank and the cost per cycle for the batteries.

Table 9 - Batteries cost for 200 kWp system.

Model	Batteries total	Unit price	Total price	Cost per cycle
OPzS solar 4600	168	1 240.00 €	208 320.00 €	69.44 €
ABSOLYTE GP Stackable	120	2 178.34 €	261 401.25 €	217.83 €
Sonnenschein A600 Solar	192	1 220.00 €	234 240.00 €	78.08 €
Sonnenschein Solar	496	375.00 €	186 000.00 €	232.50 €
CellCube	12	100 000.00 €	1 200 000.00 €	

Even though the *ABSOLYTE GP Stackable* batteries present a lower battery bank, they also present a higher final cost and cost per cycle.

The batteries that present a lower cost are the *Sonnenschein Solar* batteries, since 496 batteries constitute this bank. This is a higher number in comparison to the remaining batteries. Another negative aspect is their cost per cycle of 232.50€, a high value in comparison to the remaining batteries.

Through analysis of Table 9, we can verify that *OPzS Solar 4600* batteries are more indicated for this case. Both their final cost and the number of batteries utilized is reasonable and the cost per cycle is much lower in comparison to the remaining batteries.

6.3.3 2MWp PV system

An off-grid application with a PV hybrid system of 2 MWp and a backup diesel generator is now considered. A daily consumption of 4.09 MWh and a voltage of 400 V DC was considered for the system. This also allows for minimizing losses. The nominal capacity can be calculated with expression 33.

All the system's characteristics are represented in Table 10.

Table 10 - 2 MWp system characteristics.

System power [MWp]	2
Demand [MWh]	4.09
Autonomy [days]	1
System voltage [V]	400
DC load [MWh]	4.79
Nominal capacity [kAh]	11.97

As the system works at 400 V DC, the capacity of the battery bank will be lower in comparison to what is expected with 48 V DC.

Table 11 shows the total number of batteries in the bank, the number of strings and the number of batteries in parallel, calculated using expressions 34 and 35, respectively.

Table 11 - Batteries characteristics for 2 MWp system.

Model	Capacity [Ah]	Voltage [V]	DOD	Efficiency	C_N [Ah]	Ns	Np	Total
OPzS solar 4600	4600	2	70%		17100	200	4	800
ABSOLYTE GP Stackable	6300	2	70%		17100	200	3	600
Sonnenschein A600 Solar	3919	2	70%		17100	200	5	1000
Sonnenschein Solar	230	12	70%		17100	34	75	2550
CellCube	2083	48	100%	80%	124685	8	60	60

By analyzing Table 11, it is possible to verify that the bank of batteries would be smaller if *ABSOLYTE GP Stackable* batteries were utilized, needing only 600 batteries.

Table 12 - Batteries cost for 2 MWp system.

Model	Total	Unit price	Batteries price	Price per cycle
OPzS solar 4600	800	1 240.00 €	992 000.00 €	330.67 €
ABSOLYTE GP Stackable	600	2 178.34 €	1 307 006.27 €	1 089.17 €
Sonnenschein A600 Solar	1000	1 220.00 €	1 220 000.00 €	406.67 €
Sonnenschein Solar	2550	375.00 €	956 250.00 €	1 195.31 €
CellCube	540	100 000.00 €	54 000 000.00 €	

The *CellCube* batteries are the ideal ones for large scale applications. But their cost is still very high and will not compensate in comparison to the remaining technologies.

The batteries that present a lower final cost are the ones that present a higher cost per cycle and need more batteries for the required capacity. This is due to their small capacity and their reduced life time, in comparison to the remaining batteries.

The ideal batteries for this application are the *OPzS Solar 4600* batteries, which present a cost per cycle of 330.67 € and a total cost for a bank with 800 batteries of 992 000.00 €.

7. Conclusions

In this work an analysis and comparison of different kinds of energy storage technologies was done. This process enabled to choose the technology most suited for applications in a PV system.

The PV system has its peak of production of energy during sunlight hours. For this reason, not all storage technologies adapt to this kind of application.

All the characteristics that define the various storage technologies and their costs were considered, and we concluded that the technologies best adapted to a PV system are the conventional and flow batteries.

Within the conventional batteries, we can find *lead acid*, *Ni-Cd*, *Ni-MH*, *Zinc-air*, *SBB*, *Li-ion*, *Li-S* and *Li-air* batteries. The *lead acid* batteries are the most used in stationary applications and in PV systems. The *Ni-Cd* and *Ni-MH* batteries do not have a long life time making, therefore, their cost per cycle higher in comparison to lead acid batteries. The lithium batteries have a big potential, however, their cost is still very high. This makes them viable only for small scale applications, mainly mobile devices, due to their high specific energy. Finally, the metal-air and SBB batteries are still being developed and present very promising characteristics.

The flow batteries (VRB and ZBB) present very advantageous characteristics, in comparison with the conventional batteries. They have a 100% DOD, an almost unlimited lifetime and can make a separation between power and energy. However, this technology is still very expensive.

Three different case studies were done. The following table express the results obtained from these studies.

Table 13- Sizing results.

System power [kWp]	Autonomy [days]	System voltage [V]	C_N [Ah]	Battery	Batteries number	Cost
10	2	48	1410	Sonnenschein Solar	28	10 500.00 €
200	2	48	28477	OPzS solar 4600	168	208 320.00 €
2000	1	400	17100	OPzS solar 4600	800	992 000.00 €

For a PV hybrid system of 10 kWp off-grid, the *Sonnenschein Solar* batteries were chosen with a total cost of 10 500.00€. The battery bank consisted of 28 batteries, with a nominal capacity of 1410 Ah and autonomy of two days.

For a PV hybrid system of 200 kWp, connected to the grid, 168 *OPzS solar 4600* batteries were considered for a battery bank with a nominal capacity of 28477 Ah, autonomy of two days and a total cost of 208 320.00€.

Finally, for the case of an off-grid with a PV hybrid system of 2 MWp and a backup diesel generator, a battery bank was calculated with 800 *OPzS solar 4600* batteries, with a nominal capacity of 17100 Ah and a total cost of 992 000.00€.

8. References

[1] - http://www.intechopen.com/books/energy-storage-technologies-and-applications/techno-economic-analysis-of-different-energy-storage-technologies. Withdrawn 15/09/2014.

[2] - http://www.portal-energia.com/dimensionamento-do-controlador-de-carga-para-um-sistema-solar/. Withdrawn 25/11/2014.

[3] - Ibrahim, H., A. Içinca and J. Perron, 2008. *Energy storage systems – Characteristics and comparisons*. Canada: Renewable and Sustainable Energy Reviews 12 (2008) 1221-1250.

[4] - Bolund, Björn, Hans Bernhoff and Mats Leijon, 2005. *Flywheel energy and power storage systems*. Sweden: Renewable and Sustainable Energy Reviews 11 (2007) 235-258.

[5] - http://large.stanford.edu/courses/2010/ph240/barile2/. Novembro de 2014.

[6] - http://greenterrafirma.com/solar-thermal-for-electricity.html. Withdrawn 24/11/2014.

[7] – Siegel, Nathan P., 2012. *Thermal energy storage for solar power production*. USA: WIREs Energy Environ, 1: 119-131 doi: 10.1002/wene.10.

[8] - “Lithium-ion rechargeable battery – discharge mechanism” image, 2014. http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery1.htm.

[9] - Honsberg, H., 2008. ELEG620: *Solar Electric Systems*.

[10] – Messeger, Roger A. and Jerry Ventre, 2003. *Photovoltaic System Engineering*, 2nd, CRC Press, Washington. 60

[11] – Shukla, A. K., S. Venugopalan, B. Hariprakash, 2001. *Nickel – based rechargeable batteries*. India:Journal of Power Sources 100 (2001), 125-148.

[12] – Fetcenko, M. A., S.R. Ovshinsky, B. Reichman, K. Young, C. Fierro, J. Koch, A. Zallen, W. Mays, T. Ouchi, 2007. *Recent advances in NiMH battery technology*. USA: Journal of Power Sources 165 (2007) 544-551.

[13] – EOS Energy Storage, 2014. Introductory Briefing.

[14] – Soloveichik, Grigorii L., 2011. *Battery technologies for large-scale stationary energy storage*. Doi: 10.1146/ annurev-chembioeng-061010-114116.

[15] – DOE/EPRI 2013. *Electricity storage handbook in collaboration with NRECA*. Sandia National Laboratories. Pg. 29-109.

[16] – Ibrahim, Hussein, Adrian Ilinca, 2013. *Techno-economic analysis of different energy storage e technologies*. http://dx.doi.org/10.5772/52220.

[17] - http://www.ncbi.nlm.nih.gov/pubmed/25081362. November 2014.

[18] - https://www.semiconportal.com/en/archive/news/main-news/111026-ngk-nas-battery.html. Withdrawn 24/11/2014.

[19] - Scrosati, Bruno, Jürgen Garche, 2009. *Lithium Batteries: Status, prospects and future*. Italy: Journal of Power Sources 195 (2010) 2419–2430.

[20] – Chen, Lin, Leon L. Shaw, 2014. *Recent advances in lithium-sulfur batteries*. USA: Journal of Power Sources 267 (2014) 770-783.

[21] - http://www.gizmag.com/lithium-sulfur-battery-energy-density/29907/. Withdrawn 11/11/2014.

[22] – Padbury, Richard, Xiangwu Zhang, 2011. *Lithium-oxygen batteries – Limiting factors that affect performance*. USA: Journal of Power Sources 196 (2011) 4436-4444.

[23] – Imanishi, Nobuyuki, Osamu Yamamoto, 2013. *Rechargeable lithium-air batteries: characteristics and prospects*. Japan: http://dx.doi.org/10.1016/j.mattod.2013.12.004.

[24] – Kraytsberg, Alexander, Yair Ein-Eli, 2010. *Review on Li-air batteries – Opportunities, limitations and perspective*. Israel: Journal of Power Sources 196 (2011) 886-893.

[25] - Weber, Adam Z., Matthew M. Mench, Jeremy P. Meyers, Philip N. Ross, Jeffrey T. Gostick, Quinghua Liu, 2011. *Redox-flow batteries: a review*. J Appl Electrochem, 41:1137–1164. DOI: 10.1007/s10800-011-0348-2.

[26] - http://energystorage.org/energy-storage/technologies/redox-flow-batteries. Withdrawn 13/11/2014.

[27] - http://solarenergyengineering.asmedigitalcollection.asme.org/article.aspx?articleid=1731893. Withdrawn 19/11/2014.

[28] - http://energystoragedemo.epri.com/cec/zbb/tech_desc.asp. Withdrawn 19/11/2014.

[29] - http://www.nmsea.org/Curriculum/7_12/electrolysis/electrolysis.htm. Withdrawn 17/09/2014.

[30] - http://americanhistory.si.edu/fuelcells/basics.htm. Withdrawn 17/09/2014.

[31] - http://upload.wikimedia.org/wikipedia/commons/3/3e/EERE_Fuel_Cell_Comparison_Chart2.png. Withdrawn 17/09/2014.

[32] - http://energystoragesense.com/superconducting-magnetic-energy-storage-smes/. Withdrawn 25/11/2014..

[33]- http://energystoragesense.com/supercapacitors/. Withdrawn 25/11/2014.

[34] - http://www.albertatechfutures.ca/RDSupport/EnvironmentandCarbonManagement/CarbonCaptureStorageandCleanEnergy/CleanEnergy/ElectricEnergyStorage.aspx. Withdrawn 15/09/2014.

[35] - http://www.intechopen.com/books/energy-storage-technologies-and-applications/techno-economic-analysis-of-different-energy-storage-technologies. Withdrawn 15/09/2014.

[36] - http://www.evconversion.co.nz/sustainability/vehicle-to-grid-technology/. Withdrawn 15/09/2014.

[37] - http://ofrioquevemdosol.blogspot.pt/2014/05/franca-autoconsumo-de-energia-solar_22.html. Withdrawn 11/12/2014.

[38] - http://www.bine.info/en/publications/projektinfos/publikation/multifunktionale-wechselrichter/. Withdrawn 04/12/2014.

[39] - http://www.nacleanenergy.com/articles/16088/the-unique-advantage-pv-battery-storage-gives-commercial-buildings. Withdrawn 04/12/2014.

[40] - http://www.nature.com/srep/2014/140122/srep03815/full/srep03815.html. Withdrawn 11/11/2014.

[41] - http://www.hydrogenfuturetoday.com/car.html. Withdrawn 17/12/2014.

[42] – “Time-delayed self-consumption isolated from the grid”. *Self-consumption Solutions*, Circutor, Spain.

[43] - *IBESA Renewable Energies and Electricity Storage Report - Technologies and Markets- European Edition*, 2013. EuPD Research.

[44] - http://www.energymanagertoday.com/global-energy-storage-projects-top-700-087896/. Withdrawn 26/01/2015.

[45] - http://www.energymanagertoday.com/stationary-storage-fraction-of-advanced-battery-market-097419/. Withdrawn 26/01/2015.

[46] - http://www.energymanagertoday.com/energy-storage-in-commercial-buildings-market-to-reach-7-5bn-in-2022-089368/. Withdrawn 26/01/2015.

9. Annex A – Theoretical characteristics of storage technologies

Table 14 - Theoretical characteristics of storage technologies [14,16,43].

Technology		Power rating	Discharge time	Specific energy (Wh/kg)	
				Theory	Pratical
PHS		100-5000 MW	1-24 h+		0.5-1.5
Flywheels		0-1 MW	Milliseconds-15 min		10-30
CAES		5-400 MW	1-24 h+		30-60
Secondary batteries	Lead-acid	0-20 MW	Seconds-hours	170	30-50
	NiCd	0-40 MW		315	50-75
	NiMH				60-120
	SBB	50 kW-8 MW		755	150-240
	L-ion	0-100 kW	Minutes-hours	560	75-200
	Li-S			2500	200-300
	Li-air		Seconds-24 h+	12000	1000
	Zinc-air			1084	
Flow batteries	VRB	30 kW-3 MW	Seconds-hours	34	10-25
	ZBB	50 kW-2 MW		217	30-50
	PSB				30
Fuel Cells		0-50 MW	Seconds-24 h+		800-10000
SMES		100 kW-10 MW	milliseconds-8 s		0.5-5
EDLC		0-300 kW	milliseconds-60 min		2.5-15

Technology		Specific power (W/kg)	Efficiency (%)	Life time	
				years	cycles
PHS			75-80	40-60	>10000
Flywheels		400-1500	>90	20	100000
CAES			50	20-40	>5000
Secondary batteries	Lead-acid	75-300	70-80	5-15	500-3000
	NiCd	150-300	60-70	10-20	2000-2500
	NiMH		66		500-1000
	SBB	150-230	75-90	10-15	2500
	L-ion	150-315	85-98	5-15	1000-10000+
	Li-S				1000
	Li-air				
	Zinc-air		75	30	10000
Flow batteries	VRB		75-85	5-10	12000+
	ZBB		65-75		2000+
	PSB		77		
Fuel Cells		500+	40-50	5-15	1000+
SMES		500-2000	97	20+	100000+
EDLC		500-5000	>90	20+	100000+

Technology		Self-discharge per day	Capital cost			
			€/kW		€/kWh	
PHS		very small	519	3600	4	87
Flywheels		100%	216	303	865	4327
CAES		small	346	110	78	173
Secondary batteries	Lead-acid	0.1-0.3%	260	519	173	200
	NiCd	0.2-0.6%	433	1298	692	1298
	NiMH	0.3%	200	500	166	200
	SBB	~20%	865	2000	260	433
	L-ion	0.1-0.3%	151	3462	433	2164
	Li-S	0.3-0.5%				
	Li-air	very small				
	Zinc-air				138	
Flow batteries	VRB	small	2500	2600		1000
	ZBB		606	2164	130	865
	PSB					
Fuel Cells		almost zero		8655		
SMES		10-15%	173	400	865	8655
EDLC		20-40%	87	400	260	1731

10. Annex B - Batteries characteristics

Table 15 - Batteries characteristics.

Type	Model	Supplier	Reference	Storage capacity [Ah]	Voltage [V]	Energy [kWh]
FLA	Exide classic	GNB Industrial power	OPzS solar 4600	4600	2	
VRLA	ABSOLYTE GP Stackable		1-100G99	6300	2	
	Sonnenschein A600 Solar		A602/3920 Solar	3919	2	
	Sonnenschein Solar		S12/230A	230	12	
VRB	CellCube	Gildemeister energy solutions	FB 10	2083	48	100
ZBB	Redflow ZBM	RedFlow advanced energy storage		170	48	

Type	Model	Power [kW]	Battery price	Cost [€/kWh]	Lifetime [cycles]	DOD
FLA	Exide classic		1 240.00 €	134.78	3000	60%
VRLA	ABSOLYTE GP Stackable		2 178.34 €	172.88	1200	80%
	Sonnenschein A600 Solar		1 220.00 €	155.65	3000	60%
	Sonnenschein Solar		375.00 €	135.87	800	60%
VRB	CellCube		100 000.00 €	1000		100%
ZBB	Redflow ZBM	3				100%

Type	Model	Efficiency	Operational costs [€/kWh.cycles]	Discharge rate [hours]	Operating temperature [ºC]	Height [mm]
FLA	Exide classic		0.07	120	-40 - 50	812
VRLA	ABSOLYTE GP Stackable		0.18	100		218
	Sonnenschein A600 Solar		0.09	120		816
	Sonnenschein Solar		0.28	100		238
VRB	CellCube	80%				2403
ZBB	Redflow ZBM	80%			5 - 45	

Type	Model	Installed length [mm]	Width [mm]	Area [m2]	Volume [m3]	Self-Discharging
FLA	Exide classic	225	580	0.131	0.106	
VRLA	ABSOLYTE GP Stackable	1080	26.38	0.028	0.006	0.5-1% per week
	Sonnenschein A600 Solar	214	578	0.124	0.101	low
	Sonnenschein Solar	518	274	0.142	0.034	
VRB	CellCube	4500	2200	9.900	23.790	low
ZBB	Redflow ZBM					

10.1 Classic OPzS Solar Battery Datasheet

Network Power > Classic Solar > Classic OPzS Solar > **Benefits**

GNB Industrial Power

Classic OPzS Solar
Energy storage for outstanding power applications

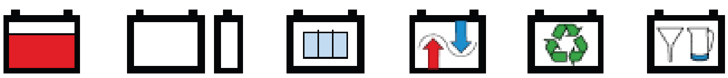
The Classic OPzS Solar range has been well proven for decades in medium and large power requirements. Due to their robustness, long design life and high operational safety they are ideally suitable for use in solar and wind power stations, telecommunications, power distribution companies, railways and many other safety equipment power supplies. The wide range of available capacities and sizes provides a solution for every power need, even in harsh environments.

Your benefit:

- **Optimised design for renewable energy applications** – highest cycling ability and long life
- **Special alloy and large electrolyte reserve** – very long topping up intervalls
- **Low maintenance** – saving costs
- **Completely recyclable** – low CO_2-footprint

Specifications

- Nominal capacity (C_{120} at 25 °C): 70.0 - 4600 Ah
- Very thick tubular positive plates for the most demanding applications
- Up to 2800 cycles at 60 % depth of discharge (C_{10}) with IU charging profile at 20 °C. For enhanced performance and for systems ≥ 48 V we recommend IUI charging to reach 3000 cycles and more.
- Designed in accordance with IEC 61427 and IEC 60896-11
- Screw connectors for a better contact and reliability
- Also available in dry-charged version with separate electrolyte
- High quality transparent containers for easy maintenance



Nominal Capacity 70.0 – 4600 Ah | Block battery/ Single cell | Tubular plate | up to 3000*+ cycles at 60 % depth of discharge | Recyclable | Low maintenance

*Using IUI charging at 20 °C

3

Network Power > Classic Solar > Classic OPzS Solar > **Technical Data**

GNB Industrial Power

Classic OPzS Solar
Technical Data

Technical characteristics and data

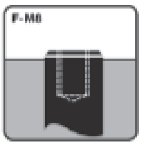
Type	Part number	Nom. voltage V	Nominal capacity C_{120} 1.85 Vpc 25 °C Ah	Length (l) max. mm	Width (b/w) max. mm	Height* (h) max. mm	Installed length (L) max. mm	Weight incl. acid approx. kg	Weight acid** approx. kg	Internal resistance mOhm	Short circuit current A	Terminal	Pole pairs
OPzS Solar 190	NVSL020190WC0FA	2	190	105	208	395	115	13.7	5.20	1.45	1400	F-M8	1
OPzS Solar 245	NVSL020245WC0FA	2	245	105	208	395	115	15.2	5.00	1.05	1950	F-M8	1
OPzS Solar 305	NVSL020305WC0FA	2	305	105	208	395	115	16.6	4.60	0.83	2450	F-M8	1
OPzS Solar 380	NVSL020380WC0FA	2	380	126	208	395	136	20.0	5.80	0.72	2850	F-M8	1
OPzS Solar 450	NVSL020450WC0FA	2	450	147	208	395	157	23.3	6.90	0.63	3250	F-M8	1
OPzS Solar 550	NVSL020550WC0FA	2	550	126	208	511	136	26.7	8.10	0.63	3250	F-M8	1
OPzS Solar 660	NVSL020660WC0FA	2	660	147	208	511	157	31.0	9.30	0.56	3650	F-M8	1
OPzS Solar 765	NVSL020765WC0FA	2	765	168	208	511	178	35.4	10.8	0.50	4100	F-M8	1
OPzS Solar 985	NVSL020985WC0FA	2	985	147	208	686	157	43.9	13.0	0.47	4350	F-M8	1
OPzS Solar 1080	NVSL021080WC0FA	2	1080	147	208	686	157	47.2	12.8	0.43	4800	F-M8	1
OPzS Solar 1320	NVSL021320WC0FA	2	1320	212	193	686	222	59.9	17.1	0.30	6800	F-M8	2
OPzS Solar 1410	NVSL021410WC0FA	2	1410	212	193	686	222	63.4	16.8	0.27	7500	F-M8	2
OPzS Solar 1650	NVSL021650WC0FA	2	1650	212	235	686	222	73.2	21.7	0.26	7900	F-M8	2
OPzS Solar 1990	NVSL021990WC0FA	2	1990	212	277	686	222	86.4	26.1	0.23	8900	F-M8	2
OPzS Solar 2350	NVSL022350WC0FA	2	2350	212	277	836	222	108	33.7	0.24	8500	F-M8	2
OPzS Solar 2500	NVSL022500WC0FA	2	2500	212	277	836	222	114	32.7	0.22	9300	F-M8	2
OPzS Solar 3100	NVSL023100WC0FA	2	3100	215	400	812	225	151	50.0	0.16	12800	F-M8	3
OPzS Solar 3350	NVSL023350WC0FA	2	3350	215	400	812	225	158	48.0	0.14	14600	F-M8	3
OPzS Solar 3850	NVSL023850WC0FA	2	3850	215	490	812	225	184	60.0	0.12	17000	F-M8	4
OPzS Solar 4100	NVSL024100WC0FA	2	4100	215	490	812	225	191	58.0	0.11	17800	F-M8	4
OPzS Solar 4600	NVSL024600WC0FA	2	4600	215	580	812	225	217	71.0	0.11	18600	F-M8	4
[illegible]	[illegible]	[illegible]	[illegible]	273	204	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	F-M8	1
OPzS Solar 350	NVSL060350WC0FA	6	350	381	204	358	391	56.0	20.0	2.39	2800	F-M8	1
OPzS Solar 420	NVSL060420WC0FA	6	420	381	204	358	391	63.0	20.0	1.96	3106	F-M8	1
OPzS Solar 70	NVSL120070WC0FA	12	70.0	273	204	358	283	35.0	15.0	18.1	688	F-M8	1
OPzS Solar 140	NVSL120140WC0FA	12	140	273	204	358	283	45.0	14.0	9.26	1314	F-M8	1
OPzS Solar 210	NVSL120210WC0FA	12	210	381	204	358	391	64.0	19.0	6.46	1884	F-M8	1

Type	C_6 1.75 Vpc	C_{10} 1.80 Vpc	C_{12} 1.80 Vpc	C_{24} 1.80 Vpc	C_{48} 1.80 Vpc	C_{72} 1.80 Vpc	C_{100} 1.85 Vpc	C_{120} 1.85 Vpc	C_{240} 1.85 Vpc
OPzS Solar 190	122	132	134	145	165	175	185	190	200
OPzS Solar 245	159	173	176	190	215	230	240	245	260
OPzS Solar 305	203	220	224	240	270	285	300	305	320
OPzS Solar 380	250	273	277	300	330	350	370	380	400
OPzS Solar 450	296	325	330	355	395	420	440	450	470
OPzS Solar 550	353	391	398	430	480	515	540	550	580
OPzS Solar 660	422	469	477	515	575	615	645	660	695
OPzS Solar 765	492	546	555	600	670	710	750	765	805
OPzS Solar 985	606	700	710	770	860	920	970	985	1035
OPzS Solar 1080	669	773	784	845	940	1000	1055	1080	1100
OPzS Solar 1320	820	937	950	1030	1150	1230	1295	1320	1385
OPzS Solar 1410	888	1009	1024	1105	1225	1305	1380	1410	1440
OPzS Solar 1650	1024	1174	1190	1290	1440	1540	1620	1650	1730
OPzS Solar 1990	1218	1411	1430	1550	1730	1850	1950	1990	2090
OPzS Solar 2350	1573	1751	1770	1910	2090	2200	2300	2350	2470
OPzS Solar 2500	1667	1854	1875	2015	2215	2335	2445	2500	2600
OPzS Solar 3100	2080	2318	2343	2520	2755	2910	3040	3100	3250
OPzS Solar 3350	2268	2524	2550	2740	2985	3135	3280	3350	3520
OPzS Solar 3850	2592	2884	2915	3135	3430	3615	3765	3850	4040
OPzS Solar 4100	2775	3090	3125	3355	3650	3840	4000	4100	4300
OPzS Solar 4600	3099	3451	3490	3765	4100	4300	4500	4600	4850
OPzS Solar 280	203	206	229	250	296	304	287	294	338
OPzS Solar 350	245	257	284	311	374	383	355	364	424
OPzS Solar 420	284	309	322	354	420	432	408	417	482
OPzS Solar 70	55.0	51.5	63.7	69.4	78.4	79.8	81.0	82.7	92.9
OPzS Solar 140	95.4	103	108	118	141	145	136	139	162
OPzS Solar 210	131	154	162	177	206	217	203	210	234

Capacities in Ah (C_6 – C_{240} at 25 °C)

* Includes installed connector, the above mentioned height can differ depending on the used vent(s).
** Acid density d_N = 1.24 kg/l

Terminal and torque



12 Nm for blocks;
20 Nm for cells

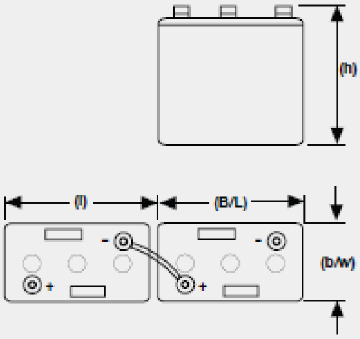
Data are also valid for dry charged version.
Change »**W**« (Wet) to »**D**« (Dry) in the part number.
E.g.:
> **filled and charged:** NVSL120070 **W** C0FA
> **dry charged:** NVSL120070 **D** C0FA

Network Power > Classic Solar > Classic OPzS Solar > **Drawings**

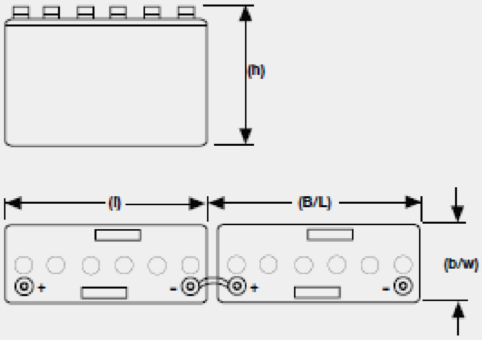
Classic OPzS Solar
Drawings

Drawings with terminal position

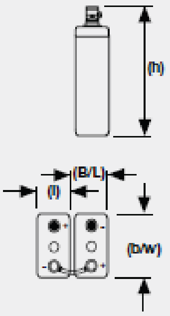
6 V Blocks



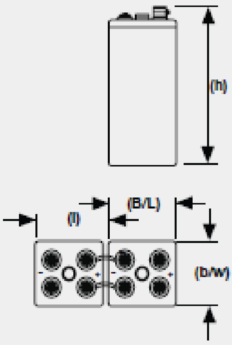
12 V Blocks



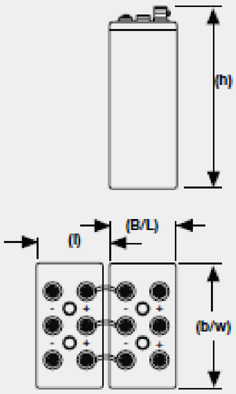
OPzS Solar 190 – OPzS Solar 1080



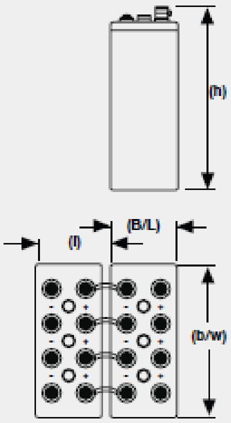
OPzS Solar 1320 – OPzS Solar 2500



OPzS Solar 3100 – OPzS Solar 3350



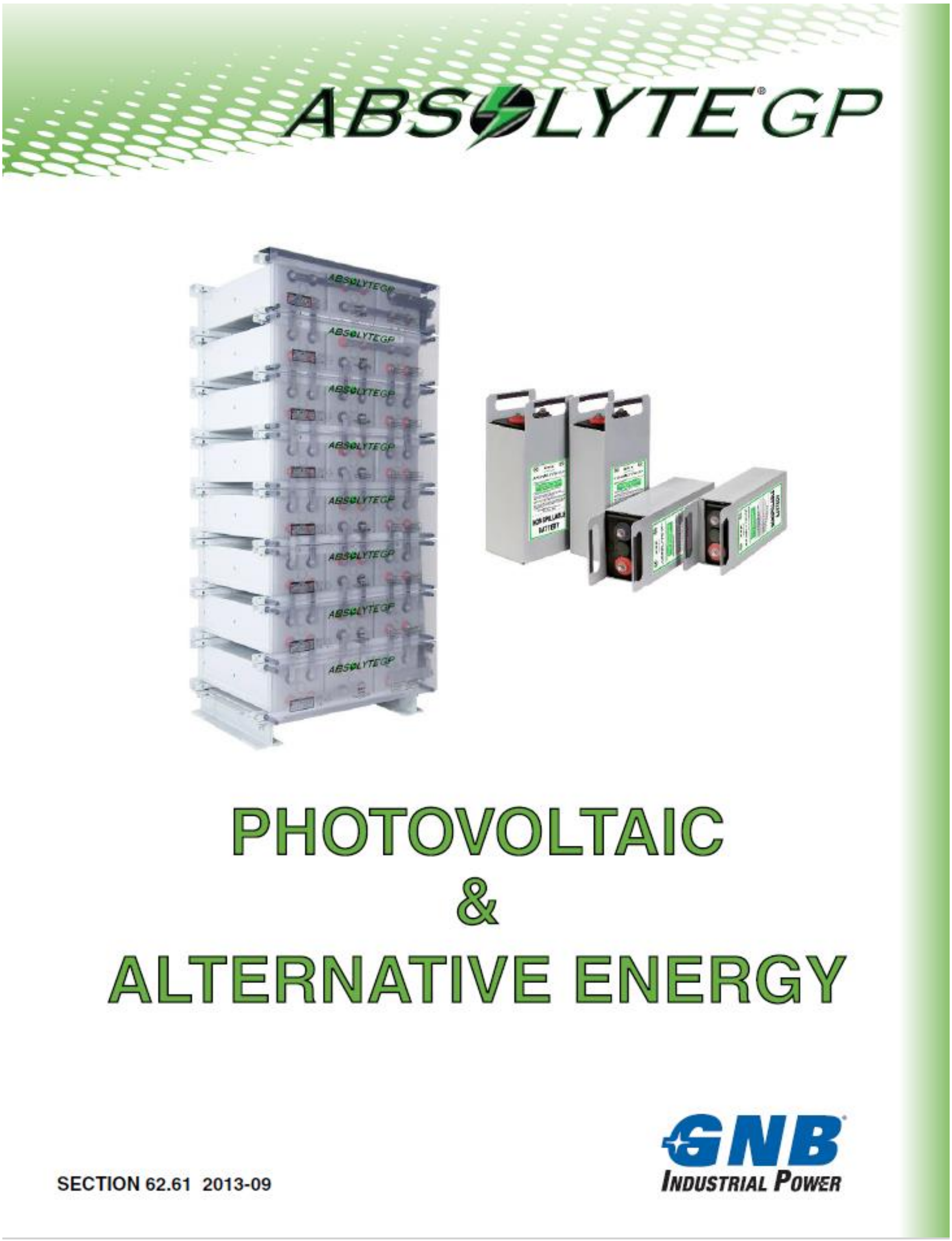
OPzS Solar 3850 – OPzS Solar 4600



Not to scale!

5

10.2 ABSOLYTE GP Battery Datasheet



Page 1

ABSOLYTE® GP

A WORLD LEADER IN VALVE REGULATED LEAD ACID (VRLA) BATTERY POWER FOR PHOTOVOLTAIC AND ALTERNATIVE ENERGY APPLICATIONS

- Proven Field Experience Since 1983.
- The Absolyte was developed by GNB® Industrial Power, a division of Exide Technologies, in conjunction with Sandia National Laboratories, as the first VRLA, large capacity, deep-cycle battery for photovoltaic applications.
- Patented lead-calcium-tin-sliver positive grid alloy provides excellent cycle life for photovoltaic applications.
- Provides for extended partial state of charge operation and allows for deep discharge recovery.
- Wide band of temperature operation — retains more capacity in cold temperatures than traditional flooded batteries.
- Modular steel tray design provides excellent heat dissipation in high temperature applications.
- Housed in protective steel trays designed for maximum installation flexibility.
- Single cell modules are available that simplify transport to remote locations.
- Eliminates the need for periodic water additions as found in flooded cells. Periodic visual inspections, voltage readings, and connection retorquing is all that is required.
- Enhanced Post Access for maintenance and battery health assessment.
- Absolyte GP is qualified to stack horizontally up to eight high for use in 1997 UBC/2001 CBC Seismic Zone IV (at or below grade).
- UL Recognized, ISO 9001:2000, NEBS Level 3 Certified in Certain Configurations.

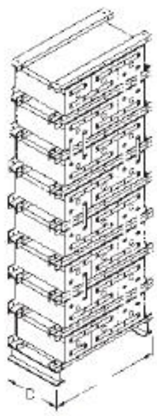
APPLICATIONS

Absolyte GP batteries are ideal for photovoltaic and alternative energy applications including:

- Village Electrification
- Telecommunications
- Residential Power
- Railroad Signal
- Navigational Aids

ADDED FEATURES AND BENEFITS

- Extended partial state of charge operation
- Deep discharge recovery
- Freezing tolerant
- Does not require separate battery room
- Recombination efficiency greater than 99%
- Globally recyclable design
- Single cell and stackable modules are available
- Simple cell replacement capability



ASSEMBLY CONFIGURATIONS

Horizontal Stack Assembly
Depth is overall, including module cover assembly. Add 102mm (4") for bottom I-beam supports to determine total height of assembled horizontal stack.

Page 2

ABSOLYTE® GP

Absolyte GP Stackable Module Weights and Dimensions

MODULE TYPE	VOLTS	NOM AH CAP (100 HR)	STACKING DIMENSIONS						UNPACKED WEIGHT		DOMESTIC PACKED WEIGHT		EXPORT PACKED WEIGHT	
			LENGTH		HEIGHT		DEPTH							
			IN	MM	IN	MM	IN	MM	LBS	KG	LBS	KG	LBS	KG
50G														
6-50G05	12	140	17.19	437	8.53	217	16.22	412	157	71	176	80	228	104
6-50G07	12	210	21.69	551	8.53	217	16.22	412	209	95	228	104	280	127
6-50G09	12	290	26.19	665	8.53	217	16.22	412	252	114	271	123	323	147
6-50G13	12	430	35.19	894	8.53	217	16.22	412	356	162	381	173	433	197
90G														
6-90G07	12	360	21.69	551	8.53	217	23.56	599	316	143	335	152	413	187
6-90G09	12	480	26.19	665	8.53	217	23.56	599	396	180	415	188	493	224
6-90G11	12	600	30.69	780	8.53	217	23.56	599	477	216	502	228	581	264
6-90G13	12	720	35.19	894	8.53	217	23.56	599	557	253	582	264	661	300
6-90G15	12	840	39.69	1008	8.59	218	23.56	599	637	289	668	303	747	339
100														
3-100G13	6	790	19.93	506	8.53	217	26.38	670	328	149	356	162	436	198
3-100G15	6	920	22.18	563	8.59	218	26.38	670	374	170	408	185	489	222
3-100G17	6	1000	24.50	622	8.59	218	26.38	670	424	192	446	202	528	240
3-100G19	6	1100	26.75	679	8.59	218	26.38	670	470	213	491	223	574	260
3-100G21	6	1300	29.00	737	8.59	218	26.38	670	515	234	539	245	623	283
3-100G23	6	1400	31.25	794	8.59	218	26.38	670	561	255	589	267	674	306
3-100G25	6	1500	33.50	851	8.59	218	26.38	670	608	276	637	289	723	328
3-100G27	6	1700	35.75	908	8.59	218	26.38	670	653	296	684	310	772	350
3-100G29	6	1800	38.00	965	8.59	218	26.38	670	704	319	736	334	824	374
3-100G31	6	1900	40.25	1022	8.59	218	26.38	670	750	340	783	355	873	396
3-100G33	6	2100	42.50	1080	8.59	218	26.38	670	795	361	829	376	920	417
1-100G39	2	2370	19.93	506	8.53	217	26.38	670	328	149	356	162	436	198
1-100G45	2	2760	22.18	563	8.59	218	26.38	670	374	170	408	185	489	222
1-100G51	2	3000	24.50	622	8.59	218	26.38	670	424	192	446	202	528	240
1-100G57	2	3300	26.75	679	8.59	218	26.38	670	470	213	491	223	574	260
1-100G63	2	3900	29.00	737	8.59	218	26.38	670	515	234	539	245	623	283
1-100G69	2	4200	31.25	794	8.59	218	26.38	670	561	255	589	267	674	306
1-100G75	2	4500	33.50	851	8.59	218	26.38	670	608	276	637	289	723	328
1-100G81	2	5100	35.75	908	8.59	218	26.38	670	653	296	684	310	772	350
1-100G87	2	5400	38.00	965	8.59	218	26.38	670	704	319	736	334	824	374
1-100G93	2	5700	40.25	1022	8.59	218	26.38	670	750	340	783	355	873	396
1-100G99	2	6300	42.50	1080	8.59	218	26.38	670	795	361	829	376	920	417

* Includes 77 mm (3") additional for Module Cover Assembly. For V-0 models, add a V suffix (example 3-100G33V).

NOTE: Design and/or specifications are subject to change without notice. If questions arise, contact your local GNB sales representative for clarification.

Page 3

ABSOLYTE® GP

CELL SPECIFICATIONS
140-6300 AH @ 100 Hour Rate

Container and Cover — Polypropylene.

Flame retardant UL94 V-0/28% L.O.I. is optional.

Separators — Spun glass, microporous matrix.

Safety Vent — 3-10 psi opening pressure, self-resealing.

Terminals — Solid copper insert.

Positive Plate — Patented Lead-Calcium-Tin-Silver grid alloy.

Negative Plate — Lead-Calcium grid alloy.

Operating Temperature — Temperature excursions between -40°C (-40°F) to +50°C (122°F) allowed (battery performance and life will be affected).

Cycle Life — 1200 cycles at 80% D.O.D. [at 25°C (77°F)] when operated per the I&O Manual.

Self Discharge — 0.5 to 1.0% per week maximum at 25°C (77°F).

Charge Controller Upper Voltage Settings— at 25°C (77°F) with a maximum charge current of 5% of nominal C/100 Amp-hour rating.

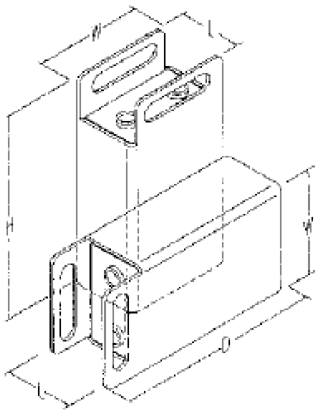
2.28 ± 0.02 V.P.C. @ 0-2% D.O.D.
2.33 ± 0.02 V.P.C. @ 3-5% D.O.D.
2.38 ± 0.02 V.P.C. @ >5% D.O.D.

For other temperatures and charge currents, contact GNB for recommendations.

Absolyte GP Single Cell Module Weights and Dimensions

CELL TYPE	NOM AH CAP (100 HR)	LENGTH		WIDTH		DEPTH OR HEIGHT		UNPACKED WEIGHT		DOMESTIC PACKED WEIGHT		EXPORT PACKED WEIGHT	
		IN	MM	IN	MM	IN	MM	LB	KG	LB	KG	LB	KG
50G													
50G05	140	3.80	97	6.49	165	16.00	406	32	15	35	16	44	20
50G07	210	3.80	97	6.49	165	16.00	406	39	18	41	19	51	23
50G11	370	4.55	116	6.49	165	16.00	406	50	23	53	24	61	28
50G13	430	5.30	135	6.49	165	16.00	406	58	26	61	28	69	31
50G15	510	6.05	154	6.55	166	16.00	406	66	30	69	31	77	35
50G19	660	7.67	195	6.67	169	16.00	406	91	41	95	43	112	51
50G27	950	10.67	271	6.67	169	16.00	406	124	56	130	59	147	67

NOTE: Design and/or specifications subject to change without notice. If questions arise, contact your local GNB sales representative for clarification.



10.3 Sonnenschein SOLAR Battery Datasheet

Network Power > **Product overview**

GNB® Industrial Power

Industrial Batteries
The powerful range of Network Power

Energy storage solutions for critical systems that require uninterrupted power supply. GNB® Industrial Power offers powerful batteries for your individual needs. The below table is only indicative and depends on customers' specific applications. For more information please ask a GNB sales representative.

Applications	Battery ranges																		
	Sonnenschein						Marathon		Sprinter			Absolyte	Powerfit	Classic					
	A400/ A600	A400 FT	A500	A700	Solar	RAIL	M FT	M/L/XL	S	P/XP	XP-FT	GP/GX	S300	GRoE	OCSM	OPzS	Energy Bloc/OGi	Solar	rail
Telecom	●	●	●	●			●	●	●		●	●			●	●	●		
UPS		●	●	●			●	●	●	●	●	●			●		●		
Emergency lighting	●		●					●		●			●			●	●		
Security	●		●	●						●			●		●	●			
Utility	●	●		●			●	●	●		●	●		●	●	●	●		
Railways	●	●	●	●		●	●	●	●		●	●			●		●		●
Photovoltaic					●							●						●	
Universal	●	●	●	●			●	●	●	●	●	●	●		●	●	●		

The GNB Network Power brand overview

ABSOLYTE® MARATHON® Sprinter® Powerfit®

> VRLA batteries (**V**alve **R**egulated **L**ead **A**cid) in which the electrolyte is fixed in an absorbent glass mat (AGM)
> Excellent high current capability
> Very economical
> Maintenance-free (no topping up)

Sonnenschein

> VRLA batteries (**V**alve **R**egulated **L**ead **A**cid) in which the electrolyte is fixed in a gel (dryfit technology)
> Inventor of Gel technology
> Highest reliability, even in non-optimal conditions
> Particularly suitable for cyclic applications
> Maintenance-free (no topping up)

Classic®

> Conventional lead-acid batteries with liquid electrolyte
> Extreme reliability, proven over decades
> Low maintenance

> Further information about service is available on page 10

2

Network Power > Sonnenschein SOLAR > **Benefits**

GNB Industrial Power

Sonnenschein SOLAR
The compact alternative for smaller solar applications

Sonnenschein SOLAR batteries are specially designed for small to medium performance requirements in leisure and consumer applications. The advantages of the maintenance free VRLA-batteries are enhanced by the worldwide excellent reputation and technical image of the dryfit technology.

Your benefits:

> **Excellent cycling performance** – 800 cycles at 60% Depth of Discharge C_{10} (at 20 °C)

> **dryfit Gel** – VRLA technology

> **Lowest energy consumption** – saving costs

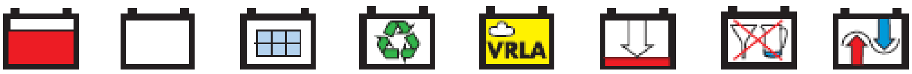
> **Robust design** – resilient in harsh conditions

> **Proof against deep discharge** – greater long-term energy delivery

> **Completely recyclable** – low CO_2 footprint

Specifications:

> Nominal capacity 6.60 – 230 Ah C_{100} (20 °C)
> Long shelf life up to 2 years at 20 °C without recharge due to the very low self discharge rate
> Designed in accordance with IEC 61427 and IEC 60896-21/22
> Manufactured in Europe in our ISO 9001 certified production plants
> Trouble-free transport of operational blocks, no restrictions for rail, road, sea and air transportation (IATA, DGR, clause A67)
> Approval: UL (Underwriter Laboratories)



Nominal capacity 6.60 – 230 Ah C_{100} | Block battery | Grid plate | Recyclable | Valve regulated lead-acid batteries | Proof against deep discharge | Maintenance-free (no topping up) | 800 cycles at 60 % DoD C_{10}

3

Network Power > Sonnenschein SOLAR > **Technical data**

Sonnenschein SOLAR
Technical data

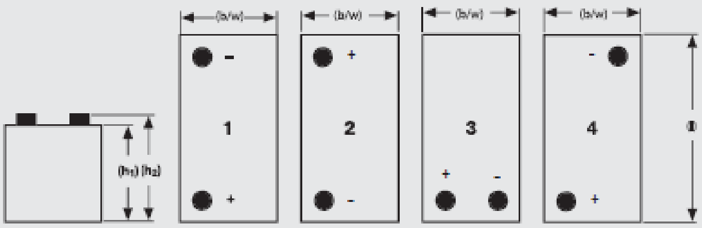
Technical characteristics and data

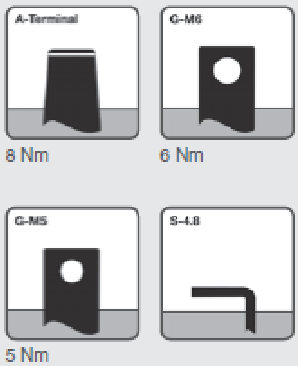
Type	Part number	Nom. voltage V	Nominal capacity C_{100} 1.80 Vpc 20 °C Ah	Discharge current I_{100} A	Length (l) max. mm	Width (b/w) max. mm	Height up to top of cover (h1) max. mm	Height including connectors (h2) max. mm	Weight approx. kg	Terminal	Terminal position
S12/6.6 S	NGS0120606HS0SA	12	6.60	0.06	152	65.5	94.5	98.4	2.60	S-4.8	3
S12/17 G5	NGS0120017HS0BA	12	17.0	0.17	181	76.0	-	167	6.10	G-M5	1
S12/27 G5	NGS0120027HS0BA	12	27.0	0.27	167	176	-	126	9.60	G-M5	1
S12/32 G6	NGS0120032HS0BA	12	32.0	0.32	197	132	160	184	11.1	G-M6	2
S12/41 A	NGS0120041HS0CA	12	41.0	0.41	210	175	-	175	14.2	A-Terminal	1
S12/60 A	NGS0120060HS0CA	12	60.0	0.60	261	136	208	230	18.1	A-Terminal	1
S12/85 A	NGS0120085HS0CA	12	85.0	0.85	353	175	-	190	26.8	A-Terminal	1
S12/90 A	NGS0120090HS0CA	12	90.0	0.90	330	171	213	236	29.2	A-Terminal	2
S12/130 A	NGS0120130HS0CA	12	130	1.30	286	269	208	230	37.5	A-Terminal	4
S12/230 A	NGS0120230HS0CA	12	230	2.30	518	274	216	238	67.0	A-Terminal	3

Capacities C_1 - C_{100} (20 °C) in Ah

Type	C_1 1.70 Vpc	C_5 1.70 Vpc	C_{10} 1.70 Vpc	C_{20} 1.75 Vpc	C_{100} 1.80 Vpc
S12/6.6 S	2.90	4.60	5.10	5.70	6.60
S12/17 G5	9.30	12.6	14.3	15.0	17.0
S12/27 G5	15.0	22.1	23.5	24.0	27.0
S12/32 G6	16.9	24.4	27.0	28.0	32.0
S12/41 A	21.0	30.6	34.0	38.0	41.0
S12/60 A	30.0	42.5	47.5	50.0	60.0
S12/85 A	55.0	68.5	74.0	76.0	85.0
S12/90 A	50.5	72.0	78.0	84.0	90.0
S12/130 A	66.0	93.5	104	110	130
S12/230 A	120	170	190	200	230

Drawings with terminal position, terminal and torque





Not to scale!

4

10.4 Sonnenschein A600 SOLAR Battery Datasheet

Network Power > Sonnenschein A600 SOLAR > **Benefits**

GNB INDUSTRIAL POWER

Sonnenschein A600 SOLAR

Unmatched dryfit Gel technology for renewable energy storage

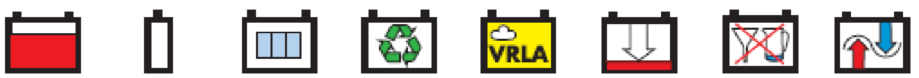
Sonnenschein A600 SOLAR is a premium range, developed specifically for applications where cycling is required. It has extraordinary energy-saving features in addition to robust reliability, proven for decades in many installations worldwide.

Your benefits:

- > **Exceptional cycling performance** – 3000+ cycles* at 60 % Depth of Discharge C_{10}
- > **dryfit Gel** – VRLA technology
- > **Lowest energy consumption** – saving costs
- > **Strong tubular plate technology** – for longer life in the toughest conditions
- > **Proof against deep discharge** – greater long-term energy delivery
- > **Horizontal mounting possible** – easy installation and maintenance
- > **Completely recyclable** – low CO_2 footprint

Specifications:

> Nominal capacity 294 – 3919 Ah C_{120} (20°C)
> Cycling performance at 20 °C (with IU charging): 2400 cycles at 60 % Depth of Discharge (C_{10}) at 20 °C
For enhanced performance and for systems ≥ 48 V we recommend IUI charging, to reach 3000+ cycles at 20 °C
> Designed in accordance with IEC 61427 and IEC 60896-21/22
> Long shelf life up to 2 years at 20 °C without recharge due to the very low self discharge rate
> Also available as flame-retardant version on request (V0)
> Manufactured in Europe in our ISO 9001 certified production plants
> Trouble-free transport of operational cells, no restrictions for rail, road, sea and air transportation (IATA, DGR, clause A67)
> Approval: UL (Underwriter Laboratories)



Nominal capacity 294 – 3919 Ah C_{120} | Single cell | Tubular plate | Recyclable | Valve regulated lead-acid batteries | Proof against deep discharge | Maintenance-free (no topping up) | 3000+ cycles* at 60 % DoD C_{10}

*With IUI charging, at 20 °C

7

Network Power > Sonnenschein A600 SOLAR > **Technical data**

GNB INDUSTRIAL POWER

Sonnenschein A600 SOLAR
Technical data

Technical characteristics and data

Type	Part number	Nom. voltage V	Nominal capacity C_{120} 1.85 Vpc 20 °C Ah	Discharge current I_{120} A	Length (l) max. mm	Width (b/w) max. mm	Height up to top of cover (h1) max. mm	Height incl. connectors (h2) max. mm	Weight approx. kg	Terminal	Pole pairs
A602/295 SOLAR	NGS6020295HS0FC	2	294	2.45	105	208	357	399	19.0	F-M8	1
A602/370 SOLAR	NGS6020370HS0FC	2	367	3.05	126	208	357	399	23.0	F-M8	1
A602/440 SOLAR	NGS6020440HS0FC	2	440	3.66	147	208	357	399	27.0	F-M8	1
A602/520 SOLAR	NGS6020520HS0FC	2	519	4.32	126	208	473	515	30.0	F-M8	1
A602/625 SOLAR	NGS6020625HS0FC	2	623	5.19	147	208	473	515	35.0	F-M8	1
A602/750 SOLAR	NGS6020750HS0FC	2	727	6.05	168	208	473	515	39.0	F-M8	1
A602/850 SOLAR	NGS6020850HS0FC	2	845	7.06	147	208	648	690	49.0	F-M8	1
A602/1130 SOLAR	NGS6021130HS0FC	2	1126	9.42	212	193	648	690	66.0	F-M8	2
A602/1415 SOLAR	NGS6021415HS0FC	2	1408	11.7	212	235	648	690	80.0	F-M8	2
A602/1695 SOLAR	NGS6021695HS0FC	2	1689	14.1	212	277	648	690	95.0	F-M8	2
A602/1960C SOLAR	NGS6021960HS0FC	2	1994	16.3	212	277	717	759	115	F-M8	2
A602/2600 SOLAR	NGS6022600HS0FC	2	2613	21.7	216	400	775	816	160	F-M8	3
A602/3270 SOLAR	NGS6023270HS0FC	2	3266	27.2	214	489	774	816	198	F-M8	4
A602/3920 SOLAR	NGS6023920HS0FC	2	3919	32.6	214	578	774	816	238	F-M8	4

Capacities C_1 - C_{120} (20 °C) in Ah

Type	C_1 1.67 Vpc	C_3 1.75 Vpc	C_5 1.77 Vpc	C_{10} 1.80 Vpc	C_{24} 1.80 Vpc	C_{48} 1.80 Vpc	C_{72} 1.80 Vpc	C_{100} 1.85 Vpc	C_{120} 1.85 Vpc
A602/295 SOLAR	124	167	193	217	248	273	289	285	294
A602/370 SOLAR	155	209	241	272	310	342	362	357	367
A602/440 SOLAR	186	251	289	326	372	410	434	428	440
A602/520 SOLAR	229	307	342	379	435	471	503	505	519
A602/625 SOLAR	275	369	410	455	523	565	604	606	623
A602/750 SOLAR	321	431	479	531	610	659	705	707	727
A602/850 SOLAR	368	520	614	681	729	782	827	822	845
A602/1130 SOLAR	491	694	818	908	973	1043	1102	1096	1126
A602/1415 SOLAR	614	867	1023	1135	1216	1304	1378	1370	1408
A602/1695 SOLAR	737	1041	1228	1362	1459	1565	1654	1644	1689
A602/1960C SOLAR	867	1222	1371	1593	1803	1942	2016	1957	1994
A602/2600 SOLAR	1047	1548	1782	2024	2276	2472	2599	2547	2613
A602/3270 SOLAR	1309	1935	2227	2530	2846	3090	3249	3184	3266
A602/3920 SOLAR	1571	2322	2673	3036	3415	3708	3899	3821	3919

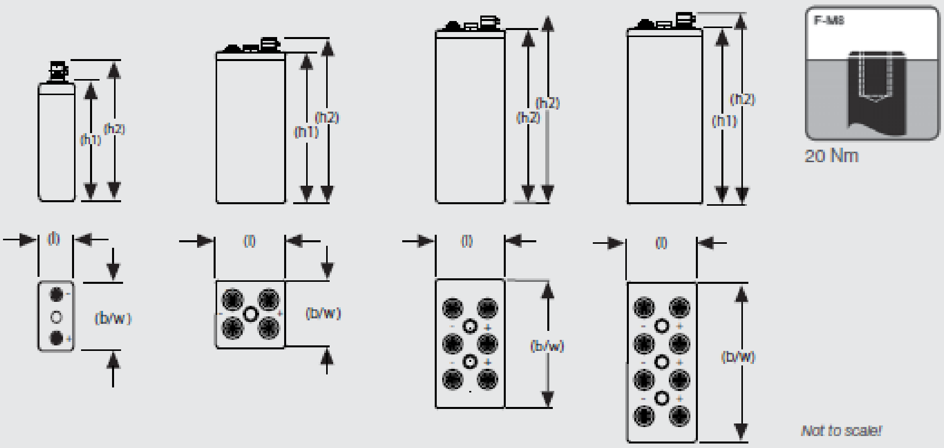
8

Network Power > Sonnenschein A600 SOLAR > **Drawings**

GNB INDUSTRIAL POWER

Sonnenschein A600 SOLAR

Drawings with terminal position, terminal and torque



9

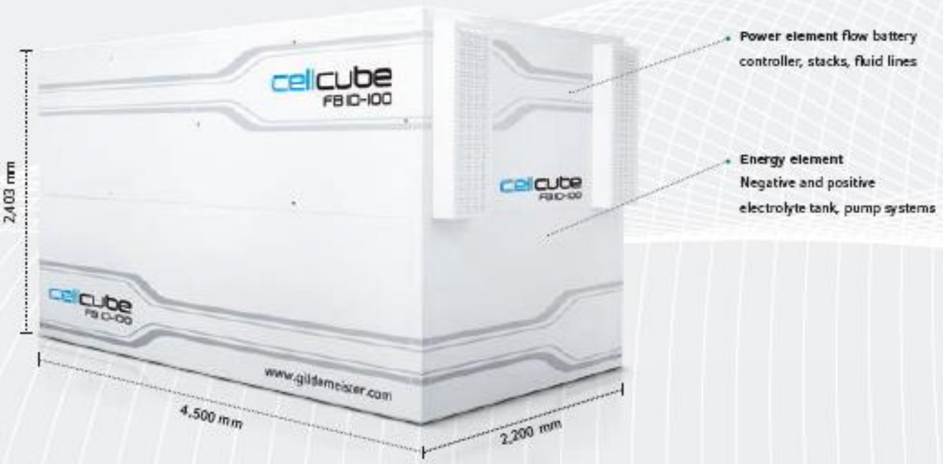
Sonnenschein

10.5 CellCube battery Datasheet

ENERGY PROVISION FROM 10 KW POWER OUTPUT AND UP TO 130 KWH CAPACITY

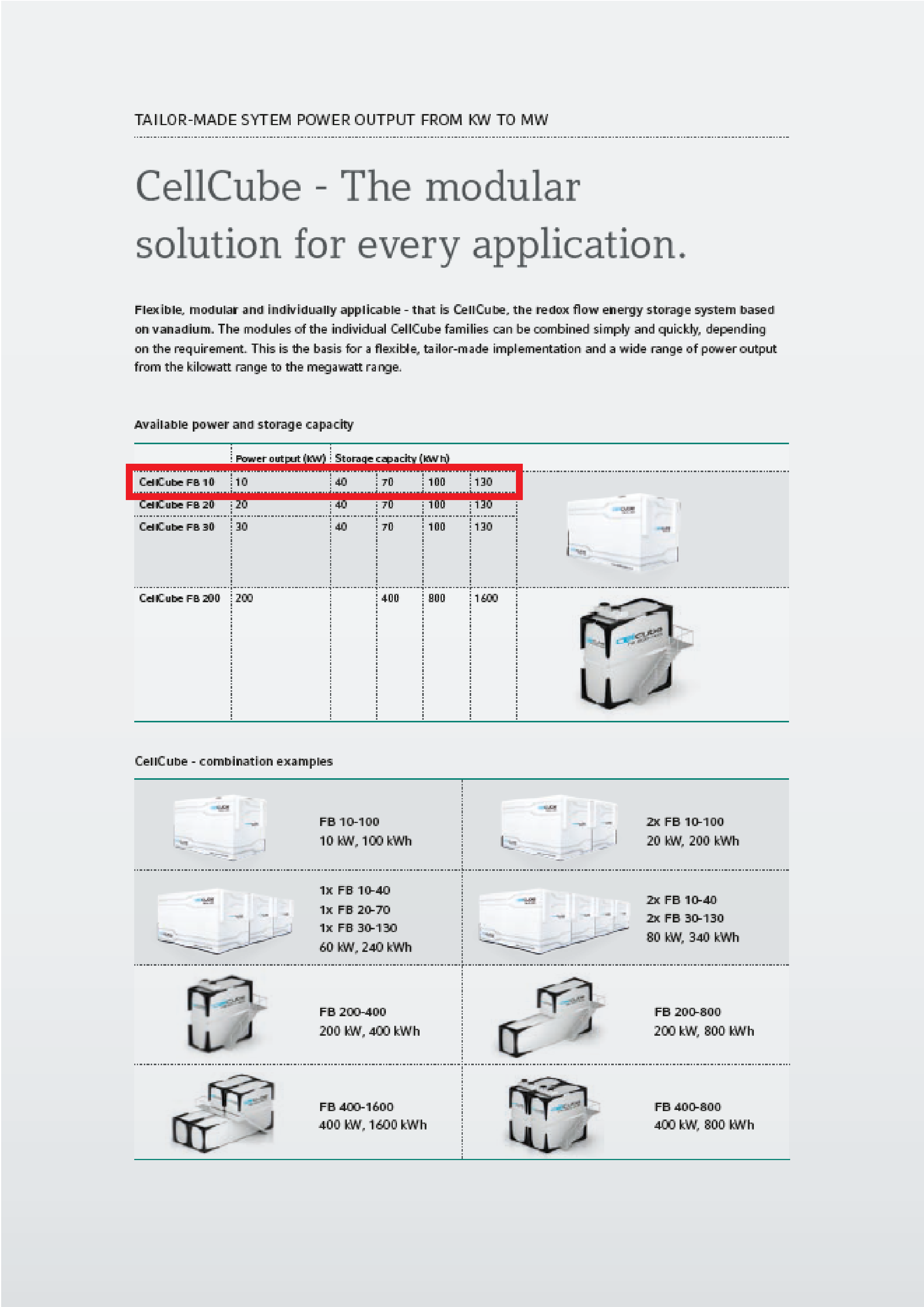
CellCube - for a stable supply of power

The low-maintenance redox flow energy storage system with its long service life, based on vanadium, guarantees uninterrupted power supply, fed by solar or wind power stations, for instance. In its weather-proof housing the CellCube can be used immediately worldwide. Clean power around the clock.



Highlights CellCube

- High safety, non-flammable, non-explosive
- Practically unlimited cycling
- Scalable up into the MW-range through simple parallel connection of multiple CellCubes
- CellCube is 100 % capable of deep discharge
- Turnkey energy storage in weatherproof and securely protected housing
- Up to 80 % efficiency
- Holistic system solution, including specially coordinated inverters, thereby allowing connection to different energy sources
- Remote or online maintenance is possible
- Central temperature management
- Optimal operational characteristics through intelligent battery management
- Standard freight containers allow simple and cost-effective transport
- Vanadium is environmentally friendly and recyclable
- Spontaneous reaction to load demand



TAILOR-MADE SYTEM POWER OUTPUT FROM KW TO MW

CellCube - The modular solution for every application.

Flexible, modular and individually applicable - that is CellCube, the redox flow energy storage system based on vanadium. The modules of the individual CellCube families can be combined simply and quickly, depending on the requirement. This is the basis for a flexible, tailor-made implementation and a wide range of power output from the kilowatt range to the megawatt range.

Available power and storage capacity

	Power output (kW)	Storage capacity (kWh)			
CellCube FB 10	10	40	70	100	130
CellCube FB 20	20	40	70	100	130
CellCube FB 30	30	40	70	100	130
CellCube FB 200	200		400	800	1600

CellCube - combination examples

FB 10-100 10 kW, 100 kWh	2x FB 10-100 20 kW, 200 kWh
1x FB 10-40 1x FB 20-70 1x FB 30-130 60 kW, 240 kWh	2x FB 10-40 2x FB 30-130 80 kW, 340 kWh
FB 200-400 200 kW, 400 kWh	FB 200-800 200 kW, 800 kWh
FB 400-1600 400 kW, 1600 kWh	FB 400-800 400 kW, 800 kWh

CELLCUBE

Technical data.

Perfomance and energy	CellCube FB 10/20/30 kW	CellCube FB 200 kW	
Nominal charge output	10/20/30 kW	200 kW	
Nominal discharge output	10/20/30 kW	200 kW	
Capacity of the energy storage system	40/70/100/130 kWh	400/800/1600 kWh	
Battery and system voltage			
Output voltage option	- 48 VDC; 120 VAC; 230 VAC (1-phase); 400 VAC (3-phase)	400 VAC	
Duration of connection / Reaction time	grid-independent: < 20 ms, remote control: < 8 ms		
Control system			
Control via external interfaces	serial, TCP / I P, bus systems		
Monitoring			
Condition detection via remote interrogation by e-mail	State of charge (SOC), available energy, charge / discharge power output, and more		
Efficiency			
Charge / discharge cycle DC	up to 80 %	up to 70 %	
Multi-stage management reduces power losses	3 independent, switchable circuits with energy-efficient pump control system	4 independent, switchable circuits with energy-efficient pump control system	
Discharge time at nominal power output		DC battery power	AC inverter power
Discharge time (autonomy)	Depends on power output and capacity		
1 hour**		220 kW	200 kVa
2 hours**		140 kW	130 kVa
3,5 hours**		110 kW	100 kVa
5 hours**		80 kW	70 kVa
Self-discharge			
Self-discharge in standby**	< 150 W	< 200 W	
Self-discharge in tank	negligible (< 1 % per year)	negligible (< 1 % per year)	
Size and weight			
Dimensions L × W × H	4,500 × 2,200 × 2,403 mm	6,000 × 2,438 × 5,792 mm*	
Weight (empty condition)	3,600 - 4,500 kg	20,000 kg	
Gross weight (filled condition)	12,800 - 14,000 kg	60,000 kg	
Climatic operating conditions			
Climatic conditions	-40°C bis +50°C (monthly average)		
	The inside temperature is controlled between 20°C and 30°C by an intelligent temperature management system. Suitable insulation (for heating and cooling) allows deployment in all climatic zones.		

* Base unit. ** Subject to change.

EMMISSION-FREE AND CLEAN ENERGY PROVISION - THE CELLCUBE TECHNOLOGY

Energy storage system CellCube.

Whether in combination with photovoltaic, wind power stations, diesel, gas and biogas generators or in parallel grid operation, CellCube is the optimal supplement to guarantee uninterrupted power supply. The stationary, large energy storage system efficiently and safely provides emission-free power, independent of climatic, weather or periodic factors.

100 %

capable of deep discharge, unlimited cycling

Redox flow energy storage system mode of operation

The liquid energy sources are stored in two tanks and pumped through the electro-chemical cells. Depending on the applied voltage, the energy sources are charged or discharged electro-chemically.
The charge controller and inverter represent the interface to the electrical energy source and the user respectively.

Vanadium redox flow principle - this is how the flow battery functions

Advantages of the vanadium redox flow battery

- Almost unlimited service life of the energy sources; system is designed for up to 20 years
- Unlimited cycles (charging / discharging) at the energy storage unit
- 100 % deep discharge
- High safety - non-flammable and non-explosive
- Low maintenance
- Power output and energy can be scaled independently of each other (modular flexibility)
- Scalable up into the MW-range through simple parallel connection of multiple CellCubes
- Self-discharge is negligible
- Only one battery element - therefore no cross-contamination
- Homogeneous energy medium
- Vanadium is a widespread raw material


cellcube
FB 200-400
cellcube
FB 200-400
cellcube
FB 10-100
Negative electrolyte tank
Fluid lines
Positive electrolyte tank
Stacks
Flow-Battery-Controller
cellcube
Vanadium
CellCube represents best sustainability:
The vanadium flow energy storage system
exclusively uses fluid energy sources with
dissolved vanadium salts. They are not
subject to ageing and can be used without
limitation - this is optimal resource
management. Conventional batteries are
subject to wear and tear through loss of
reactive material. Vanadium flow energy
storage system do not contain any problem
substances like lead, cadmium or mercury
and are neither flammable nor explosive.

10.6 Redflow Batteries Datasheet

redflow
advanced energy storage

RedFlow ZBM

THE ZINC BROMIDE FLOW BATTERY

"RedFlow's zinc-bromide flow battery module, the RedFlow ZBM, is a fully flexible solution for multi-hour stationary energy storage applications. The RedFlow ZBM has been designed with superior lifetime energy throughput at a low cost."

BENEFITS

- Full DC solution
- Inherently safe design
- Flexible use for system integrators
- Series and parallel configurations
- Easily maintained to extend life
- Recyclable

Performance

RedFlow's ZBM is a high-performance battery that provides high energy density and best performance in deep discharging applications. RedFlow ZBMs operate at 100% and partial depths of discharge without degradation. It features longer life, lower life-cycle costs and a superior temperature range of operations.

Safe and Recyclable Design

The design of a RedFlow ZBM capitalises on the unique ability to stop reactions and isolate the electrolyte in the tanks. Electrical safety is enhanced by a unique current-limiting capability in the event of a short circuit. On-board intelligence continually monitors the condition of the battery, and shuts the battery down on detection of any abnormalities. The RedFlow ZBM is comprised of low-cost, predominantly recyclable materials, being principally plastic, metal and organic electrolytes.

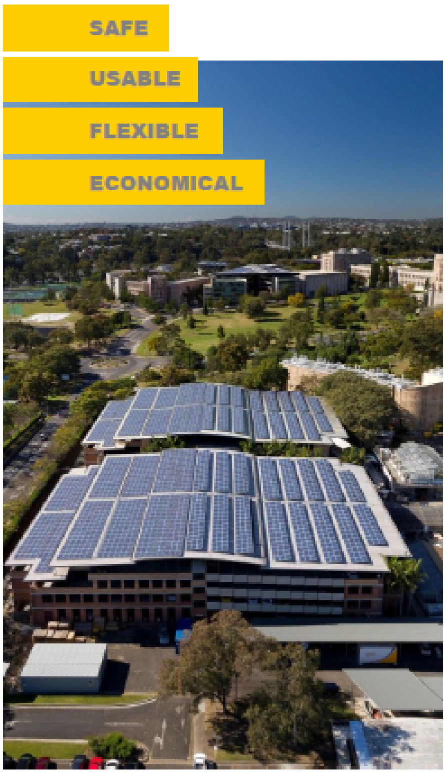
Flexibility

As the only zinc-bromide battery designed as an OEM product, the RedFlow ZBM has all the inherent attributes of a standard battery, with the advantages of embedded control for discrete operation, e.g. configurable as constant power or constant current. It can be customised to specific applications. The RedFlow ZBM has an open-source MODBUS communications system, and will work with off-the-shelf control and power electronics.

Versatile

As a scalable modular building block, single or multiple RedFlow ZBMs can be used in parallel or series arrays, enabling flexible voltage and capacity configurations from ~8kWh to MWh.

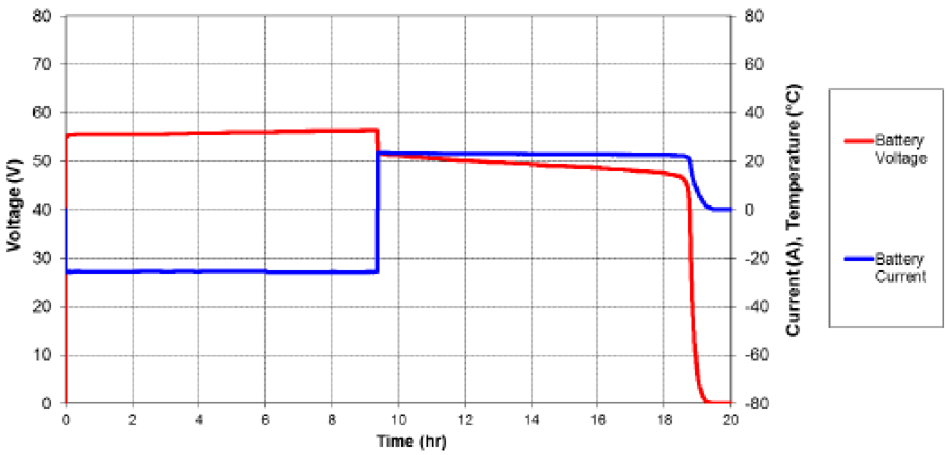
www.redflow.com



Technical Specifications

Power	3 kW continuous / 5 kW peak
Energy	8 kWh, 170 Ah (duty cycle dependant)
Dimensions	845 L x 823 H x 400 W (mm) 33 L x 32 H x 16 W (in)
Weight	225 kg (500 lb) with electrolyte 90 kg (200 lb) without electrolyte
Electrolyte Volume	100L (26 Gal)
Net Energy Efficiency	80% DC-DC Max
DC Operating Range	42 – 58 V
Ambient Operating Temperature	5 to 45 °C (Operation limited from 45°C, shut down at 50°C)
Shelf Life	Indefinite with no temperature effect
Communication	RS485, MODBUS®
Certifications	Pending: C-Tick, CE, FCC, UL Certifications
Safety Datasheet	DG Class 8 for electrolyte

Typical Charge and Discharge Curve



About RedFlow

RedFlow is a leading developer and manufacturer of zinc-bromide flow batteries. RedFlow's standard 3kW/8kWh zinc-bromide battery module (ZBM) is designed to be flexible and integrated into electricity storage systems for a range of stationary applications.

RedFlow Limited

27 Counihan Road
Seventeen Mile Rocks
Brisbane, QLD 4073
AUSTRALIA

Suite C3,
11601 Pellicano Dr.
El Paso,
TX 79936, USA.

Phone: +61 7 3376 0008
Fax: +61 7 3378 3751
Email: info@redflow.com

www.redflow.com

11. Annex C - Sizing

Table 16 - 10 kWp sizing.

Type	Model	Capacity [Ah]	Voltage [V]	DOD	Efficiency
FLA	OPzS solar 4600	4600	2	70%	
VRLA	ABSOLYTE GP Stackable	6300	2	70%	
	Sonnenschein A600 Solar	3919	2	70%	
	Sonnenschein Solar	230	12	70%	
VRB	CellCube	2083	48	100%	80%
ZBB	Redflow ZBM	170	48	100%	80%

Model	CN [Ah]	Ns	Np	Total
OPzS solar 4600	1410	24	1	24
ABSOLYTE GP Stackable	1410	24	1	24
Sonnenschein A600 Solar	1410	24	1	24
Sonnenschein Solar	1410	4	7	28
CellCube	1234	1	1	1
Redflow ZBM	1234	1	8	8

Model	Unit price	Total price	Area [m2]	Volume [m3]
OPzS solar 4600	1 240.00 €	29 760.00 €	0.131	0.106
ABSOLYTE GP Stackable	2 178.34 €	52 280.25 €	0.028	0.006
Sonnenschein A600 Solar	1 220.00 €	29 280.00 €	0.124	0.101
Sonnenschein Solar	375.00 €	10 500.00 €	0.142	0.034
CellCube	100 000.00 €	100 000.00 €	9.900	23.790

Model	Total Area [m2]	Total Volume [m3]	Lifetime [cycles]	Cost per cycle
OPzS solar 4600	3.132	2.543	3000	9.92 €
ABSOLYTE GP Stackable	0.684	0.149	1200	43.57 €
Sonnenschein A600 Solar	2.969	2.422	3000	9.76 €
Sonnenschein Solar	3.974	0.946	800	13.13 €
CellCube	9.900	23.790		

Table 17- 200 kWp sizing.

Type	Model	Capacity [Ah]	Voltage [V]	DOD	Efficiency
FLA	OPzS solar 4600	4600	2	70%	
VRLA	ABSOLYTE GP Stackable	6300	2	70%	
	Sonnenschein A600 Solar	3919	2	70%	
	Sonnenschein Solar	230	12	70%	
VRB	CellCube	2083	48	100%	80%
ZBB	Redflow ZBM	170	48	100%	80%

Model	C_N [Ah]	Ns	Np	Total
OPzS solar 4600	28477	24	7	168
ABSOLYTE GP Stackable	28477	24	5	120
Sonnenschein A600 Solar	28477	24	8	192
Sonnenschein Solar	28477	4	124	496
CellCube	24918	1	12	12
Redflow ZBM	24918	1	147	147

Model	Unit price	Total price	Area [m^2]	Volume [m^3]
OPzS solar 4600	1 240.00 €	208 320.00 €	0.131	0.106
ABSOLYTE GP Stackable	2 178.34 €	261 401.25 €	0.028	0.006
Sonnenschein A600 Solar	1 220.00 €	234 240.00 €	0.124	0.101
Sonnenschein Solar	375.00 €	186 000.00 €	0.142	0.034
CellCube	100 000.00 €	1 200 000.00 €	9.900	23.790

Model	Total Area [m^2]	Total volume [m^3]	Lifetime [cycles]	Cost per cycle
OPzS solar 4600	21.92	17.80	3000	69.44 €
ABSOLYTE GP Stackable	3.42	0.75	1200	217.83 €
Sonnenschein A600 Solar	23.75	19.38	3000	78.08 €
Sonnenschein Solar	70.40	16.75	800	232.50 €
CellCube	118.80	285.48		- €

Table 18 - 2 MWp sizing.

Type	Model	Capacity [Ah]	Voltage [V]	DOD	Efficiency
FLA	OPzS solar 4600	4600	2	70%	
VRLA	ABSOLYTE GP Stackable	6300	2	70%	
	Sonnenschein A600 Solar	3919	2	70%	
	Sonnenschein Solar	230	12	70%	
VRB	CellCube	2083	48	100%	80%
ZBB	Redflow ZBM	170	48	100%	80%

Model	CN [Ah]	Ns	Np	Total
OPzS solar 4600	17100	200	4	800
ABSOLYTE GP Stackable	17100	200	3	600
Sonnenschein A600 Solar	17100	200	5	1000
Sonnenschein Solar	17100	34	75	2550
CellCube	124685	9	60	540
Redflow ZBM	124685	9	734	6606

Model	Unit price	Batteries price	Lifetime [cycles]	Price per cycle
OPzS solar 4600	1 240.00 €	992 000.00 €	3000	330.67 €
ABSOLYTE GP Stackable	2 178.34 €	1 307 006.27 €	1200	1 089.17 €
Sonnenschein A600 Solar	1 220.00 €	1 220 000.00 €	3000	406.67 €
Sonnenschein Solar	375.00 €	956 250.00 €	800	1 195.31 €
CellCube	100 000.00 €	54 000 000.00 €		- €

Model	Area [m2]	Volume [m3]	total area [m2]	Total volume [m3]
OPzS solar 4600	0.131	0.106	112.752	91.555
ABSOLYTE GP Stackable	0.028	0.006	24.616	5.366
Sonnenschein A600 Solar	0.124	0.101	160.305	130.809
Sonnenschein Solar	0.142	0.034	367.888	87.557
CellCube	9.900	23.790	5346.000	1427.382